Influence of Recycled PET Fibres on Mechanical Properties of Concrete

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Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Civil Engineering

Eastern Mediterranean University
June 2022
Gazimağusa, North Cyprus

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ABSTRACT

Plastic wastes have destructive impact on the environment and the nature is on the verge of plastic waste crisis. The only things that will determine the future of the planet are the common actions of humans. All forms of plastics used in everyday routine disposed of at the end of service life which cannot be completely recycled instantly, and thus large quantities of non-biodegrable waste are disposed to landfills every year. Recycling method is accepted as one the most environmentally reliable methods of disposing plastic waste.

Polyethylene terephthalate (PET) represents the greatest fraction among the plastic waste subsequent to polyethylene. PET is generally obtained in considerable amounts from the plastic bottles used as containers for water and other soft drinks. Due to its favourable properties such as low density, high durability, low cost and ease of fabrication, the consumption and thus the production of PET bottles has drastically increased in recent years. Therefore, the specific interest is growing currently in utilization of this waste in the form of aggregates or fibres as concrete constituents. North Cyprus is a country with no industrial demand of plastic bottles, utilization of recycled bottles in concrete applications thereby contributes towards a more environmentally sustainable mitigation method of this waste by reducing the amount of PET waste in the nature.

This study aims to investigate the mechanical properties of recycled PET fibre reinforced concrete. The main properties examined during the present work were compressive strength, tensile strengths, plastic shrinkage resistance, impact resistance and pull-out resistance. Recycled PET fibre reinforced concrete (RPFRC)specimens were prepared and tested according to related standards. PET fibres with diameters of

0.45 mm, 0.65 mm and 1.00 mm, lengths of 20 mm and 30 mm and fibre volume fractions of 0.5%, 1.0%, 1.5% and 2.0% were used in the experiments.

The results revealed that addition of fibres reduced the workability of concrete samples at fresh stage due to increasing surface area and inter particle friction. Compressive strength, tensile strength and flexural strength of RPFRC specimens were slightly higher than control specimen for several recycled PET fibre dimensions up to 1.5% volume fraction due to bridging effect of fibres. However, further increase in volume fraction has resulted in decrease according to formation of air voids due to entanglement.

The addition of recycled were observed to improve plastic shrinkage resistance of RPFRC compared to control concrete. At some points, PET fibres were eliminated all cracks formed due to plastic shrinkage. Even though no apparent effect of PET fibres was observed on the impact resistance of concrete specimens, significant effect on the ultimate failure energies were observed. Pull-out resistance tests were carried out to find-out the bonding resistance of each fibre. However, the fibre with highest surface area achieved highest pull-out strength, individual pull-out strength of fibre does not reflect the performance when applied in larger volumetric ratios.

Keywords: Recycled PET, fibre-reinforced concrete, mechanical properties, plastic shrinkage, impact energy

ÖZ

Plastik atıkların çevre üzerinde yıkıcı etkileri vardır ve doğa plastik atık krizinin eşiğindedir. Gezegenin geleceğini belirleyecek olan tek şey, insanların ortak eylemleridir. Günlük rutinde kullanılan her türlü plastik, anında geri dönüştürülemeyen kullanım ömrü sonunda bertaraf edilmekte ve bu nedenle her yıl büyük miktarlarda biyolojik olarak parçalanamayan atıklar düzenli depolama sahalarına verilmektedir. Geri dönüşüm yöntemi, plastik atıkların bertaraf edilmesinde çevre açısından en güvenilir yöntemlerden biri olarak kabul edilmektedir.

Polietilen tereftalat (PET), plastik atıklar arasında polietilenden sonra en büyük payı temsil etmektedir. PET, genellikle su ve diğer alkolsüz içecekler için kap olarak kullanılan plastik şişelerden önemli miktarlarda elde edilmektedir. Düşük yoğunluk, yüksek dayanıklılık, düşük maliyet ve üretim kolaylığı gibi olumlu özelliklerinden dolayı PET şişelerin tüketimi ve dolayısıyla üretimi son yıllarda önemli ölçüde artmıştır. Bu nedenle, beton bileşenleri olarak agregalar veya lifler şeklinde bu atığın kullanımına özel ilgi artmaktadır. Kuzey Kıbrıs, endüstriyel plastik şişe talebi olmayan bir ülkedir, beton uygulamalarında geri dönüştürülmüş şişelerin kullanılması, doğadaki PET atık miktarını azaltarak bu atığın çevresel açıdan daha sürdürülebilir bir azaltım yöntemine katkıda bulunur.

Bu çalışma, geri dönüştürülmüş PET elyaf takviyeli betonun mekanik özelliklerini araştırmayı amaçlamaktadır. Mevcut çalışma sırasında incelenen ana özellikler, basınç dayanımı, çekme dayanımı, plastik büzülme dayanımı, darbe dayanımı ve çekme dayanımıydı. Geri dönüştürülmüş PET elyaf takviyeli beton (GDPETB) numuneleri ilgili standartlara göre hazırlanmış ve test edilmiştir. Deneylerde 0.45 mm, 0.65 mm ve 1.00 mm çaplarında, 20 mm ve 30 mm

uzunluklarında ve lif hacim oranları %0.5, %1.0, %1.5 ve %2.0 olan PET elyaflar kullanılmıştır.

Sonuçlar, artan yüzey alanı ve partiküller arası sürtünme nedeniyle lif ilavesinin taze aşamada beton numunelerinin işlenebilirliğini azalttığını ortaya koymuştur. GDPETB numunelerinin basınç mukavemeti, çekme mukavemeti ve eğilme mukavemeti, liflerin köprüleme etkisinden dolayı %1.5 hacim fraksiyonuna kadar birkaç geri dönüştürülmüş PET lif boyutu için kontrol numunesinden biraz daha yüksekti. Ancak elyaflarin hacim fraksiyonundaki daha fazla artışı , elyaflarin birbirine dolanması nedeniyle oluşan hava boşluklarından dolayı azalmaya neden olmuştur.

Kontrol betonu ile karşılaştırıldığında, geri dönüştürülmüş ilavesinin GDPETB'ların plastik büzülme direncini iyileştirdiği gözlemlenmiştir. Bazı noktalarda, plastik büzülme nedeniyle oluşan tüm çatlaklar PET lifleri ile ortadan kaldırılmıştır. PET elyafların beton numunelerin darbe dayanımı üzerinde belirgin bir etkisi gözlemlenmemesine rağmen, nihai kırılma enerjileri üzerinde önemli bir etkisi gözlemlenmiştir. Her bir elyafın yapışma direncini bulmak için çekme direnci testleri yapılmıştır. Bununla birlikte, en yüksek yüzey alanına sahip elyaf, en yüksek çekme mukavemetine ulaşmıştır, elyafın tek tek çekme mukavemeti, daha büyük hacimsel oranlarda uygulandığında performansı yansıtmamaktadır.

Anahtar Kelimeler: Geri dönüştürülmüş PET, elyaf-takviyeli beton, mekanik özellikler, plastik büzülme

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my supervisor Prof. Dr. Özgür Eren for his guidance, effort, concern and support through my academic research. I am very grateful to my Thesis Monitoring Committee members Prof. Dr. Khaled Marar and Assoc. Prof. Dr. Tülin Akçaoğlu, your constructive comments and supervision helped me tremendously.

I would like to thank to the director and staff of Darem Ltd. for the procurement and cutting of the PET fibres. Also, I wish to extend my appreciation to CEE Ltd. for providing cement and other building equipment's used in concrete sample preparations.

I would like to appreciate and give a special thanks to Ogün Kılıç, engineer of Materials of Construction Laboratory for his helps and supports with all experimental instruments. I want to thank Mr. Orkan Lord, technician of Civil Engineering Laboratory for his helps during experimental tests.

I am very grateful to my dear friend and colleague Can Özgün Sayı, his collaboration and support through this academic journey was invaluable.

I would like to express my sincere gratitude to my father Metin Özaşık, my mother Keziban Özaşık and my brother Kemal Özaşık, for their support, patience and encouragement throughout my academic research.

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INTRODUCTION

1.1 General Background

Plastic is a very distinctive material due to its advantageous properties such as low cost, lightweight, durability, and versatility. Amount of commercial plastic waste around the world is increasing day by day because of high consumption products made of plastics. In 2019, the global plastic production was around 368 million metric tons (348 in 2017; [1]) and very high portion of this amount ended up landfilled or incinerated [2]. The general utilization areas of virgin plastics in Europe can been seen in Figure 1. Polyethylene terephthalate (PET) bottles were initially used in water and beverage packaging, then started gaining interests in other industries such as medicine, cleaning products and cosmetics. PET is one of the most used plastics and its production by 2020 is predicted to be approximately 73 million metric tons which makes PET waste to make up the biggest proportion amongst all plastic wastes [3]. Consequently, utilization of recycled PET waste in concrete applications can lead to diminishing of this waste and improved concrete properties. The PET recycling sector in North Cyprus is in a developing stage and demand for this waste is very low as there is very little usage area of this waste in the industry. Thus, the major proportion of the PET waste is sent to landfill or incinerated whereas the minor proportion is collected, shredded, and sent to other countries with very low profits. Therefore, utilization of recycled PET waste in concrete applications may result in a more developed recycling sector, less waste to landfills or incinerated in North Cyprus and most importantly more sustainable concrete applications can be attained.

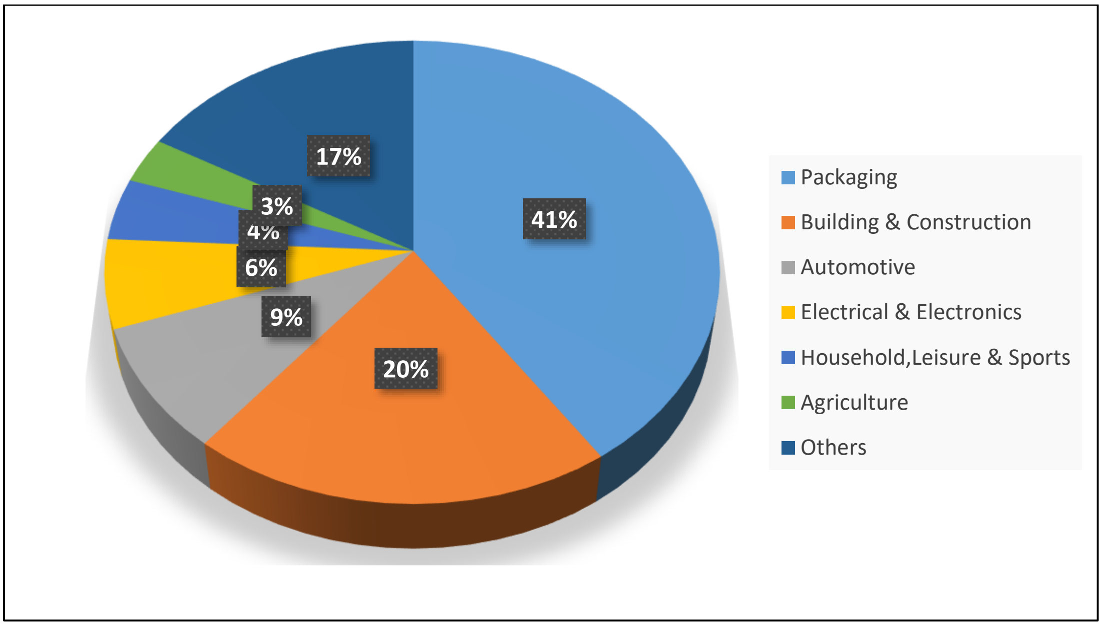


Figure 1: Distribution of European Plastic Demand. Retrieved from (Plastics Europe, 2021)

Nowadays, literature studies involve incorporation of recycled PET as aggregates or fibre reinforcements, with or without mechanical treatments in concrete or mortar [4]–[7]. Although concrete has satisfactory properties, there are some intrinsic drawbacks such as low tensile strength, low resistance against plastic shrinkage cracks and brittle feature (low ductility). Influence of recycled PET fibres on mechanical properties of concrete without replacing any other constituent in concrete has been studied by various researchers [8]–[10]. Incorporation of PET fibres in concrete provide crack control and enhance ductility, and diminish the waste disposed by incineration and landfill that are causing environmental problems.

Wide range of micro cracks tend to occur in the concrete matrix due to tensile stresses generated by various loading modes and shrinkage mechanisms. On the other hand, ‘bridging effect’ is the main function of recycled PET fibres that are used as reinforcements in concrete applications. Thus, fibres have ability of preventing propagation and diminishing the amplitude of cracks. Furthermore, this particular property of fibres offers distinct benefits such as improved post-peak ductility and energy absorption [11], [12].

Contradictory results were obtained in the literature about the effect of recycled PET fibres on the compressive strength of RPFRC. Fraternali et al., (2011), reported a high increase of compressive strength up to 35% at 1.0% volume fraction. It was also observed that the effect of fibres with lower aspect ratio (length/diameter ratio) was more significant on improving compressive strength. On the other hand, S. B. Kim et al., (2010), observed a moderate decrease from 1% to 9% in compressive strength with increasing fibre volume from 0.5% to 1.0%. According to a study conducted by Ochi et al., (2007), moderate increase was observed in compressive strength compared to control concrete up to 1.0% fibre content, further addition of fibres diminished the increase or even turned the result into a decrease for different water to cement (w/c) ratios. The reason for these variations in results can be ascribed to different geometries and surface characteristics of recycled PET fibres.

In the study by Ochi et al., (2007), recycled PET fibres with 0.7 mm diameter and 30 mm length were manufactured from recycled PET bottles. There was a moderate increase in compressive strength up to 1.0% volume fractions, followed by a decrease upon further addition. However, PET fibres were observed to improve the bending strength significantly (25-36% depending on water to cement ratio) over control concrete at 1.5% fibre fraction. According to Pelisser et al., (2012)., fibres with diameter of 25 μm and length of 20 mm were observed to have no significant effect on compressive strength at 0.05%, 0.18% and 0.30%. On the other hand, flexural strength was improved between 13.6% and 19.2% compared to plain concrete at the same volume fractions.

Plastic shrinkage cracks are one of the main reasons for low performance in concrete applications. Pavements, bridge slabs and car parking floors are prone to plastic shrinkage cracks which occur before complete hardening of concrete, since those expansive surfaces are restrained and exposed to high moisture evaporation rates and high temperatures during placement. If the surface cracks that occur by virtue of plastic shrinkage remain undetected, these cracks act as channels for passage of external deteriorating agents, hence long term durability of concrete gets worse [14]. According to a study done by Borg et al., (2016), recycled PET fibres were found to have a favourable effect on plastic shrinkage crack reduction in concrete. Furthermore, longer PET fibres were observed to have higher performance than short PET fibres with same diameter at all fibre volume fractions. J. H. J. Kim et al., (2008) examined the effect of straight, crimped and embossed PET fibres on plastic shrinkage resistance of cement-based composites at various fibre fractions. Crimped and embossed fibres which were found to have better bond strength than straight fibres exhibited better performance in controlling cracks up to 0.5% volume fraction. However, once the fibre volume fraction was further increased, fibre geometry was observed to have no further effect on controlling cracks as the cracks were controlled by an adequate number of fibres.

Study conducted by Pelisser et al., (2012) revealed that, addition of recycled PET fibres with 25μm diameter and 20 mm length at very low volume fractions (0.05%,0.18% and 0.30%) observed to enhance the impact energy up to 2.3 times compared to plain concrete. Nevertheless, no effect of fibres on the first crack was observed.

In this present study, manufactured recycled PET fibres with three diameters (0.45mm, 0.65mm, 1.0mm), two lengths (20mm,30 mm) and four volume fractions (0.5%, 1.0%, 1.5%, 2.0%) were used in order to evaluate the influence of recycled PET fibres on the mechanical properties of concrete compared to conventional concrete. The main aim of this project is to undertake a comprehensive investigation and fill the gaps in the literature by assessing the function of fibres with regards to dimension and proportion on compressive and indirect tensile strengths of concrete. Moreover, the effect of fibres on plastic shrinkage resistance and impact resistance of RPFRCs governed by fibre dimensions and volume fractions were investigated according to related standards.

1.2 Aims and Objectives

The main aim of this study is to produce a Fibre Reinforced Concrete by incorporating recycled PET fibres and examine the influence of these fibres on the mechanical strength, plastic shrinkage resistance and impact resistance of concrete composite. Also, the another target is to enhance the utilization of PET waste in concrete applications, by encouraging the further improvements in both recycling and construction sector.

In order to reach the aims of the study mentioned above. The objectives followed are given below;

1. To conduct a comprehensive literature survey and evaluation of the previous and recent research studies and findings for collection knowledge about utilization of recycled PET fibres in the concrete applications.
2. To collect information about the PET recycling industry and management approaches of discarder PET waste in North Cyprus.

3. To check and determine the type of recycled PET fibre which is the most suitable for the preparation of recycled PET fibre reinforced concrete (RPFRC).
4. To evaluate and compare the arguments for and against on the performance of recycled PET fibre incorporated concrete mixtures.
5. To determine the thickness and length of PET fibres in order to fill in the gaps in the literature and contribute to a more comprehensive study.
6. To prepare a mix design by considering the possible effects of PET fibres and intending to utilize large quantities of PET waste.
7. To investigate the effect of different diameter and length recycled PET fibres at various volume fractions on the mechanical properties of concrete including compressive and indirect tensile strengths.
8. To study the performance of the plastic shrinkage resistance of RPFRC.
9. To evaluate the resistance of RPFRC mixtures against impact loads.
10. Finally, assessment of all the experimental results, suitable fibre dimensions and level of utilization for recycled PET fibres in concrete should be determined.

1.3 Works Done

To accomplish the outlined objectives, the following tasks were performed;

1. To keep abreast with the futuristic developments in view of post-consumer PET waste in utilization in concrete, various scientific papers and books were reviewed.
2. In order to comprehend the waste management approach and recycling technology in North Cyprus. Meetings with authorities in the government and in the plastic industry were held.

3. Since there was no PET fibre manufacturer in North Cyprus. The PET fibres were procured in the form of long monofilaments with various diameters from a hair thread company in Turkey. The monofilaments were cut into fibres in intended lengths afterwards.
4. Similar and contracting experimental findings and views were investigated to understand the behaviour of PET fibres in concrete.
5. Multiple experimental studies with varying PET fibre dimensions, volume fractions and application methods were evaluated to have a more comprehensive and useful work in order to fill in the missing gaps in the RPFRC literature.
6. BRE [16] mix design method was followed to arrange the quantity of concrete components on the mixture. Hence high volumes of PET fibres were aimed to incorporate into concrete mixtures, the slump range was preferred to be the highest.
7. Compressive strength, splitting tensile strength and flexural strength tests were conducted according to relevant standards. The influence of fibre dimensions and volume fractions was observed.
8. An environmental chamber was designed and built according to relevant standards for the evaluation of plastic shrinkage resistance of RPFRC. The investigation was carried out by measuring the crack widths on the surface of concrete specimens after complete settings was occurred.
9. Impact resistance of both control and RPFRC specimens were evaluated by adapted impact load apparatus to find out the influence of PET fibre dimension and volume.

10. Relationships between recycled PET fibre dimensions and volumes, mechanical strength, plastic shrinkage resistance and impact resistance were reviewed for suggesting the best utilization choice of recycled PET fibre dimension and maximum volume percentage into RPFRC.

1.4 Guide to Thesis

The thesis includes the following chapters;

Chapter 1: This chapter contains a general background information describing the aim of the thesis. The objectives and methodology followed in the study was outline in this chapter.

Chapter 2: Global plastic consumption, several environmental impacts and various waste management approaches were discussed in this chapter. Preliminary information about Polyethylene Terephthalate (PET) was given and post-consumer PET waste utilization methods in worldwide and in North Cyprus was reviewed.

Chapter 3: Fibre reinforced concrete was initially presented in this chapter. Many types of fibres were mentioned and their effects on the properties of fibre reinforced concrete was discussed. Influence of plastic and PET fibres observed in literature was also reviewed.

Chapter 4: This chapter include the experimental methods followed for the thesis. Concrete composition, mixing procedures and preparation of RPFRC specimens were explained.

Chapter 5: This chapter deals with the experimental findings and discussions of the tests carried out. Analyses and also comparison with literature studies were also presented.

Chapter 6: Conclusions drawn from every experimental tests carried out were presented. Moreover, recommendations for future studies were also given.

Chapter 2

ENVIRONMENTAL IMPACTS AND WASTE MANAGEMENT OF PET

2.1 Environmental and Economic Impacts of Plastics

High volumes of wastes formed and disposed of to landfills per year due to manufacturing processes, post consumption and human actions. However, these wasted are commonly managed by send to landfills that ends up with high cost and energy affiliated with landfilling and also land space depletion, can be a main restriction to the waste management. The total volume of solid waste created constantly increases and plastic wastes that form the major proportion are directly and indirectly end up in the environment. Plastic wastes are generating in high volumes and presence of these wastes is a threatening factor for our global sustainability [17]. Plastics are replacing the conventional materials such as glass, wood and metal due to their intrinsic properties such as lower cost, distinctive and flexible. [18] Recently, plastic consumption has remarkably increase which induced to accumulating plastic waste worldwide. Figure 2 illustrates the ascending progress in the plastic production globally in the last 5 years. Large volumes of non-biodegradable and chemically dis-reactive waste, especially in the form of plastic waste, have been proven to adversely effect the environment. Besides, these plastic wastes are regarded as the major threathening sources of environmental pollution [19]. Post consumed plastics can be removed by three principal methods: incineration, land-filling and re-cycling depending on the basic principles of waste management [20].

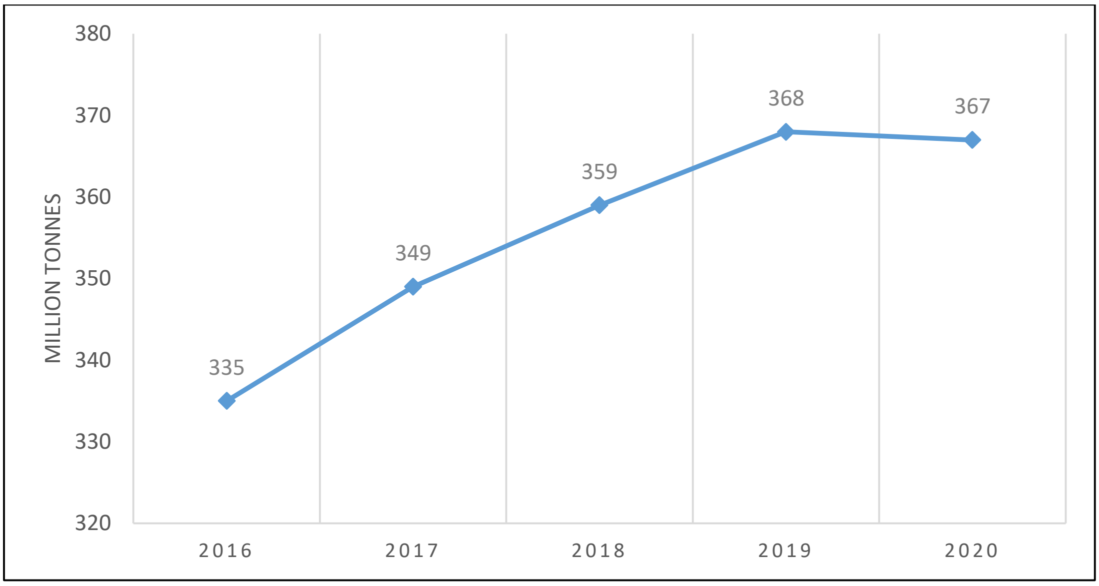


Figure 2: World Plastic Production. Retrieved from [21]

Polyethylene terephthalate (PET) is one of most used plastics specially to produce bottles for water, soft beverages, dressings, etc. In 2018, it is estimated that, 9 thousand tonnes of domestic PET waste were detected in south side of Cyprus while 11% of this amount was consist of uncollected and improperly disposed wastes. PET was also the second contributor to absolute plastic leakage after synthetic rubber with 112 tonnes leakage and leakage rate of 1.3% followed by HDPE (high density polyethylene) and LDPE (low density polyethylene). Although the total quantity of polyethylene terephthalate waste in the country was less than HDPE and LDPE, the contribution of PET to absolute plastic leakage was larger, hence placing it to second position after synthetic rubber which is the most leaking plastic. This is due to two reasons; firstly, PET had the lowest collection rate amongst all plastic polymers thus the highest improperly disposed and uncollected rate than others. Secondly, once PET waste mismanaged (improperly disposed and uncollected), it has higher release rate as the circumstance in Cyprus. Thus, PET is more prone to end up in waterways than other polymers. [22].

Water is as crucial as air for all humans. Therefore, it is essential to have drinkable clean water wherever they are at all times. The ones who don't have an access to drinkable water at their home water systems often turn out to another option; bottled water. Thus, the most used package is the PET bottle and the world consumes a million PET bottles every minute.

PET bottles may cheap and versatile, but it has high environmental consequences. From manufacturing to disposal, PET water and beverage bottles have devastating impacts on humans, climate, oceans and wildlife.

Water bottles are produced from synthetic organic polymers that derived from fossil fuel. Natural gas, crude oil and coal are the main materials in manufacturing of plastic while majority of water bottles are produced from polyethylene terephthalate resin. PET bottles production had increased globally in the last decades in order to meet the demand by the growing population. Since 1950, more than 8.3 million tonnes of plastics have been manufactured in which around 60% of plastic waste has been send to landfills and nature [23]. Some of the outlined environmental impacts of plastic wastes are explained below;

2.1.1 Ocean Pollution

Water bottles plus their caps that discarded have come at the third place at the most collected plastic trash in beach clean ups. Although it is not hard to pick up pieces and bits of bottles from the ocean, it is almost impossible to clean microplastics in the ocean. Around 8 million tons of PET plastic have found their way to oceans every year and are responsible for deaths of more than million animals and seabirds yearly. PET waste accounts for 80% of coastal debris worldwide. As water bottles degrade, microplastics start to form which produce carcinogenic toxics that put the marine life in danger. Before complete degrade of plastics, fish and seabirds eat the small pieces of plastics that results in death due to blockages, ulcers and starvation. Furthermore, many living organisms such as whales, turtles, seagulls, seals and dolphins have entangled with PET debris. If no precautions are taken, there would be more waste than fish in the oceans in the following decades [23].

2.1.2 Drain Blockage

Disposal of plastic bottles without any advanced disposal arrangement can induce serious flooding events. That occur when plastic bottles gathered together in the sewage and drainage system causing clogging. Blocking of drains creates environmental inconveniences and health issues due to accumulation of waste water outside of drainage system.

2.1.3 Landfill Occupation

PET is a very durable material but on the another hand being durable is one of its major environmental issue. PET is a non-biodegradable waste thus; it can take more than 450 years for plastic water bottles to completely decompose in nature. Moreover, landfills are restricted, and if no action take place against disposal of large quantities of these degragation resistant materials, landfills can get full rapidly.

2.1.4 Human Health

As stated above, the harmful effect of micro plastics to marine life that form during degradation of waste bottles correspondingly influence the human health. Micro plastics are carcinogenic due to their toxic nature and people can easily expose to these chemicals while eating fish, drinking water and even breathing. These substances are swallowed by fishes and absorbed by plants from the soil, thereby get into food chain. Therefore, consuming foods that include these chemical substances can harm reproductive, immune and nervous systems of humans.

2.2 Plastic Waste Management

The generally used plastics are non-biodegradable. The reason behind this behavior is that, the commonly employed monomers in plastic production, such as propylene and ethylene are produced from fossil hydrocarbons [24]. For this reason, plastic wastes pile up in dumping areas and environment rather than disintegrate. Therefore, a beneficial waste management method should be applied in order to mitigate the economic, environmental and social effect of plastic waste. An integrated waste management approach involves incineration (waste to energy conversion), landfill, recycle, reuse and reduce [25]. Reduction of plastic waste can be done in two ways, either collecting waste plastics before or after getting involved to urban waste stream. The plastic waste collected after mixing with urban waste stream are generally very contaminated and not economically appropriate for recycling. Thus, incineration and landfill are more suitable approach for these wastes. Contrarily, recycling approach is more suitable for plastic wastes that are not enter to the urban waste stream [25].

Plastic wastes can be categorized as a good source of fuel because of the high energy values of most resins almost equal to some natural energy sources. Therefore, incineration of plastic wastes provides a desirable source of alternative energy which could replace the natural resources. However, the volume of plastic waste could be reduced by almost 90-95% [25], emissions related with toxic vapors and dioxins during incineration process could raise concerns especially for those facilities that don’t fulfil the criteria to assure the conservation of environment and human health[26], [27] . Moreover, the ash residues produced by incineration contain heavy metals that can potentially pollute soil and ground water. Therefore, alternative methods of preventing leachate from these residues to contaminate the soil and ground water are required [25].

Landfilling is an another plastic waste management approach where low biodegradability of these wastes can be a matter of environmental concern [25]. However, post utilization wastes are generally discarded to landfills, land-space depletion, high annual costs and improper management of disposal are the main concerns associated with the landfilling process [17]. Disposing of plastic waste can be done in two ways; either restrained in appropriately managed sanitary landfills or left unrestrained in open dumps or in the natural habitat [24]. If landfilling is not implemented in an environmentally responsible manner (storing wastes under inadequate conditions), it could bring out environmental risks. Lightweight plastics can move from the landfill sites to environment via winds or rains and that destructive materials can enter to groundwater [26]. Recycling and incineration (energy recovery) rates have continuously risen over the last decade, which has considerably reduced landfilling [27].

Improper management of plastic wastes by landfilling and incineration without recovering energy causes reduction of natural resources and also increases the volume of waste discarded to landfills. Therefore, recycling seems to be more effective approach in terms of increasing resource recovery and decreasing environmental litter [25], [26]. Post-consumer plastics can be recycled either mechanically or chemically, depending on the composition of waste, availability and development of technologies, and their feasibility in socially and economically different natures. Mechanical recycling is the most frequently used method for recycling of plastic waste which involves firstly, classification and cleaning of collected plastic waste and then grinding it into small flakes and sometimes end up by pelletizing. This process is crucial to preserve natural resources and environment, as this waste management approach can decrease the volume of fossil fuels required for the production of commodity plastics [27]. Development of recycling technology and lessening of plastic waste is only possible if the virgin (primary) materials in plastic manufacturing are replaced by recycled polymers [24]. Worldwide recycling rate for plastic waste has been very low throughout history. It was estimated that, only 10% of the plastic waste produced globally till 2017 was recycled while 14% was incinerated and the remaining 76% was discarded to landfills, open dumps, environment and even to oceans. On the other hand, by 2018, it was estimated that less than14% of global plastic waste was recycled while 14% was incinerated and remainder was disposed of in landfills and environments [26]. In Europe, 9.4 million tonnes of post-consumer plastic waste was collected to be recycled in 2018 while the total post- consumer plastic waste was 61.8 million tonnes [2].

The another effective approach of waste management is to reuse of plastic waste in different applications. Alternatively, the reuse of post-consumer plastic wastes in the construction industry as a replacement of virgin construction materials in cement composites can be considered as a way of plastic waste disposal [19], [27]. The recycled plastic wastes commonly utilized mortar or concrete in two ways; either in a form of shredded plastic particles as a replacement of natural aggregates or in a form of fibres to enhance properties. The improvement of advanced construction material utilizing recycled plastics is an essential progress for both the plastic recycling and the construction industries [25]. If the volume of virgin plastic treated and manufactured will decrease due to reuse, the energy consumption and hazardous emissions to atmosphere will also significantly decrease [17].

2.3 Polyethylene Terephthalate

Polyethylene Terephthalate is one of the most widely used plastic products globally due to its engineering properties and potential application, and in 2018, 481.6 billion PET bottles were sold [26]. It composes almost 18% of the total polymers generated and more than 60% of generated polymer is utilized for bottles and synthetic fibres, constitutes around 30% of PET demand worldwide [28]. PET is a recyclable and transparent polymer with good impact and tensile strength [29]. As a virgin plastic, PET is used for the production of water and soft drink bottles, stuffing for pillows and bags and textile fibers while at recycled condition, PET is used for the production of detergent bottles, carpets and film packaging [25], [30]. PET waste composes the second largest proportion of waste after polyethylene in the total plastics waste stream [2], [17].

Polyethylene terephthalate is a thermoplastic polymer and belongs to a polyester family. The use of recycled PET (commonly abbreviated as Re-PET or R-PET) instead of virgin PET and bottles made up of glass substantially increases in the recent decades. Moreover, some companies started offering PET bottles with 50-100% recycled PET content, hence 1.4 million tons of packaging market in 2018 was covered by PET [30].

2.4 Sources and Recycling of PET Waste

Apart from bottles and textile fibers, PET is used extensively in the production of electronic and sporting goods, lightning and material handling equipment and household products [31]. The PET waste can be classified under three major categories: a) Water and soft drink bottles – minor problems during recycling associated with impurities and various kinds of additives used in the production. b) Films for packaging - minor problems during recycling associated with various kinds of additives used in the production and the molecular weight of PET that can influence the repeatability of products collected. c) Waste tire cord – large problems during recycling associated with contaminations due to ground rubber and metals, thus these proportion of PET waste is generally used as alternative fuel [28].

The PET recycling is a common example of most extensively practiced post-consumer waste recycling process. The post utilization PET waste recycling sector started as a response to environmental pressure in order to enhance waste management [31]. It was estimated that, the PET recycling fraction for bottles and packaging in Europe was 57% in 2014 [27]. This recycling fraction is much more than other post-consumer plastic wastes. This waste management approach composed of three process which are collection, separation and reutilizing into a product. Each country has its own waste collection method that is more suitable to themselves while each method has its own profits and drawbacks. The most critical factors are the total collected volume and the level of contamination which varies a lot between each country.

Since the PET waste was collected, it is separated from the other polluting plastic waste such as PVC, HDPE, etc. by hand or machines. Then, the separated PET waste was compacted as bales for transporting more simple. After all, these waste PET bales are reutilized into new products, mainly bottles and containers, but also converted to fibres. In order to achieve efficient reprocessing and quality, the waste PET should be refined from all impurities and contaminations [31]–[33].

However, recycling of PET waste has restrictions and challenges due to aforementioned problems, it is still most economically waste management approach to mitigate PET waste. Addition to that, low cost and modern technologies for PET recycling bring an added value to production of PET bottles and other applications from recycled PET with comparatively lower cost than virgin PET [31]. For the purpose of attaining effective PET recycling, PET flakes and pellets should meet specific minimum requirements. Moreover, these PET flakes and pellets must be released from all contaminations to enhance final properties and quality of reprocessing [27].

2.4.1 Utilization of Post-Consumer Recycled PET

As mentioned above, recycling of post-consumer PET waste can make an important contribution to environment and economy from various point of views. It helps to decrease the utilization of natural resources and environmental impacts, also saving money and energy [28] . The volume of PET waste generated increases annually, while only small fraction is recycled and landfilled and a bigger fraction of these wastes are disposed to environment [17]. Therefore, discovering new applications where PET waste can be useful may offer a sustainable waste management. Recycling of PET waste reduces the level of land and water resources pollution and add value to the PET waste by providing a route such as concrete construction for utilization of these products for various applications such as in concrete constructions [34]. PET waste can be introduced in civil engineering applications in the form of lightweight aggregate, filler and insulation. Although, there is a great opportunity for the utilization of PET in construction industry, its use and progress are very restricted [17].

During the last two decades, PET wastes have been introduced to construction in various forms as concrete and mortar constituents [4]. It can be transformed into unsaturated polyester and added to produce polymer concrete [13], can be used as replacement of or addition to natural aggregates [35], [36] and the most recent form is the use of PET waste as fibre reinforcements in concrete [13], [37].

2.4.2 Utilization of Post-Consumer Recycled PET in North Cyprus

North Cyprus is a part of very small island and currently one of the biggest concern of the islanders is the land and water resources pollution associated with plastic wastes. In 2020, post-consumer plastic wastes composed 18.4% of the total waste generated in the country and this amount is foreseen to be doubled in the upcoming decades due to growing population. Presently, the plastic waste recycling rate in North Cyprus is very low and only a negligible amount of plastic waste is recycled by private firms and organizations while majority of this waste is being disposed to landfills and open dumps (Çevre Koruma Dairesi,2020).

Turkish Republic of Northern Cyprus is an isolated island which does not have an access to many global polymer businesses. Addition to that, there is no demand for recycled PET in the island. Therefore, the majority of the PET waste is being discarded to landfills and open dumbs, causing environmental problems while only small amount is being collected, cleaned, compressed into bales and transported. Consequently, any effort made for the utilization of post-consumer recycled PET waste into concrete industry would mitigate the environmental pollution related with this waste and help to achieve environmentally and economically more sustainable waste management in North Cyprus. Figure 3 shows the waste management methods applied in each country in 2018, it can be seen that Cyprus was appeared to be one of the countries with least recycling rate. Around 80% of total plastic waste was sent to landfills [38].

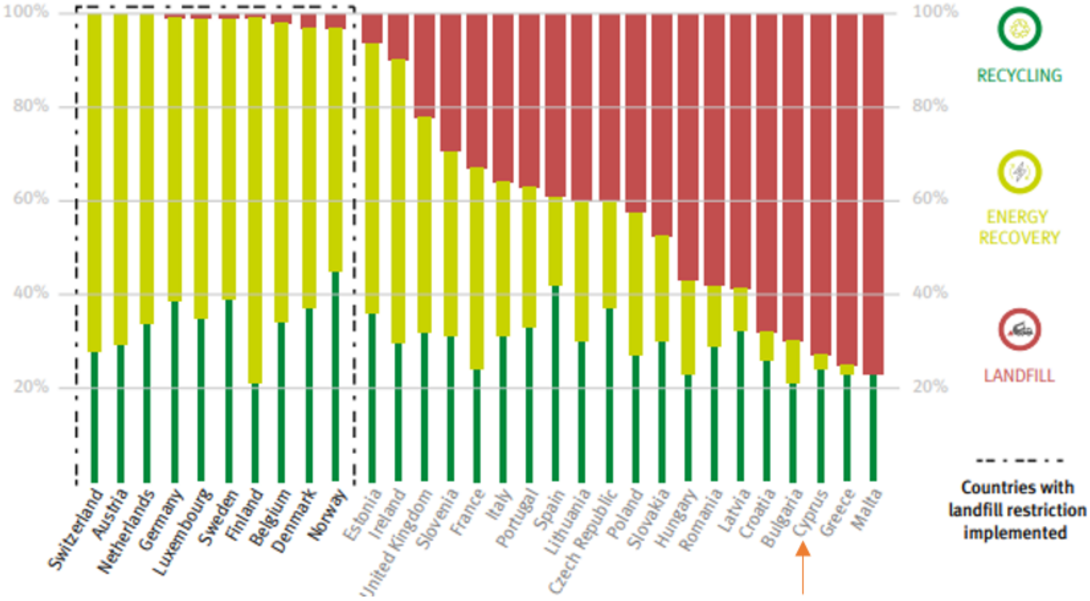


Figure 3: Post consumer plastic waste rates of landfilling, energy recovery and recycling per country in 2018. (Retrieved from Europe 2020-The Facts)

Chapter 3

FIBRE REINFORCED CONCRETE

3.1 Fibre Reinforced Concrete

Concrete is one of the most attractive building material of construction industry due to its high compressive strength, relatively low cost, ease of application and high resistance to external atmospheric agents [39], [40]. Although concrete has high compressive strength, tensile strength is one of its weaknesses. The main factor behind the low tensile strength of concrete is the formation of cracks due to plastic shrinkage [41].

However, steel bar reinforcements were used to improve tensile strength concrete, the deterioration of concrete structures may exhibit itself as cracking, flaking and peeling which is still due to inadequacy of tensile resistance [42], [43]. Moreover, the deterioration of bond between concrete and steel re-bars is also another reason of degradation of structural beam members. High inclination of steel reinforcement to corrosion against environmental conditions plays a role in weakening of flexural strength and ductility of concrete members [43].

Therefore, to overcome this drawback, an innovative concrete composite was developed which is known as fibre reinforced concrete (FRC). FRC is produced from cement, water, fine aggregate, course aggregate and sometimes admixtures. In comparison to conventional concrete, FRC usually has higher cement and fine aggregate contents and smaller size of coarse aggregates (Neville & Brooks 1987). In order to fibres function effectively, they have to be uniformly distributed within the cement composite. A number of fibres such as glass fibres, steel fibres, natural fibres and synthetic fibres were incorporated in concrete mixtures in order to enhance the properties of concrete [44].

Fibre reinforced concrete is cement composite which consists of short, discontinuous fibrous material that are uniformly distributed and randomly oriented [45], [46]. Steel, glass and plastic fibres are being used in tunnel and underground constructions as reinforcements in concrete. The utilization of fibre in concrete applications as reinforcement has been steadily increased by taking advantage of the particular characteristics of each fibre. Polyethylene (PE), polypropylene (PP), aramid, nylon and polyesters (most commonly refers to PET) are the synthetic fibres that are frequently used in concrete applications [13].

The primary task of the fibres in cement based composites is to enhance the ability of concrete members to resist loads by virtue of crack arresting capability of fibres [45]. Fibre reinforced concrete is a special form of building material while the its quality and performance varies with different concrete binder parameters and as well as the variations in fibre material types, fibre dimension, fibre concentration, orientation and distribution of fibres [47].

Although fibres are generally used in cement based composites to control plastic shrinkage cracks. They also decrease the permeability and bleeding of water [46]. Fibres were also observed to improve mechanical and physical properties of concrete composites by increasing tensile strength, flexural strength, toughness and durability properties [44]. The incorporation of fibres into concrete changes the brittle behaviour of concrete into a ductile behaviour. Fibres resist to formation and propagation of cracks, thus improve tensile strength and ultimate yield strain of cement composite [48].

The fibres are divided into two categories; the fibres which formed from natural ingredients such as asbestos, sisal and cellulose or the fibres that are manufactured materials such as steel, glass, carbon and polymer (Neville & Brooks 1987). The volumetric ratio of fibres respect to concrete volume added is generally between 1% and 5% while in most cases 3% was chosen to be the maximum [49]. Another important properties of fibres are shape and surface characteristics, length, and aspect ratio (length to diameter ratio). The workability of this type of concrete mixes reduced as the fibre volume and fibre aspect ratio increases.

The schematic diagram of Figure 4 illustrates the different failure mechanisms in fibre reinforced concrete. The first failure mode is the fibre rupture (1) and it occurs when the length of fibre is higher than the critical length (L_c). This happens due to increased surface area related to increased length of fibres result in greater bond of fibres with matrix, which prevents fibre slippage [50]. As opposed to that, fibre pull-out (2) would take place due to failure of bond between fibre and cement matrix if the fibre length is lesser than the critical length. Therefore, length of fibre was suggested to be higher the size of max. aggregate used in concrete to prevent these failure modes [39](Neville and Brooks 1987). Furthermore, fibres have an ability of bridging cracks (3) and decreases the intensity of stress that forms at the crack tips. This ability also helps to diminish crack widths and consequently prevents the ingress of water and contaminants into concrete matrix. As for fibre rupture and fibre pull-out, debonding of fibre from matrix (4), are all energy absorbing and dissipating fibre to matrix mechanisms that stabilise the propagation of cracks inside the concrete [39], [47], [51]. Fibres are also preventing the propagation of minor cracks (5) and distribute cracks to other locations on the concrete (6). Although, the contribution of each fibre to crack control is negligible, the total influence of fibre reinforcement on concrete is cumulative. Thereby, addition of fibres enhanced the drying and plastic shrinkage resistance, crack resistance and toughness of concrete [39].

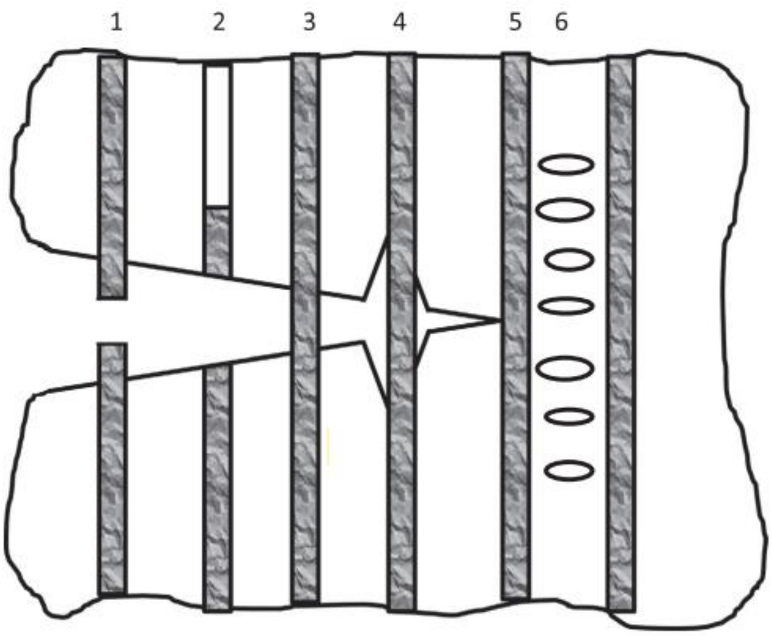


Figure 4: Energy absorbing fibre to matrix mechanisms.
Retrieved from (Yin et.al, 2015)

The most frequently used fibre to reinforce concrete is the steel fibres. Steel fibres are generally used to improve tensile and flexural strengths, resistance to surface abrasion and fatigue, and impact resistance of concrete [52], [53]. Moreover, steel fibres were observed to be efficient in controlling plastic shrinkage cracks in concrete by reducing total crack length and maximum crack width, and correspondingly reducing the total crack area [54]. Steel fibre is also a good conductor of electric, magnetic and heat which makes it very suitable for several specific applications. On the other hand, the steel fibres are prone to corrosion that can be very harmful and cause quick deterioration of reinforced members [39], [55]. In addition to enhanced crack resistance, glass fibres reinforced concrete has an advantage of lower weight compared to conventional concrete. Reduced weight of building panels leads to a decrease in size of supporting columns and cost, and longer available spaces between shrinkage joints [42]. In contrast, glass fibres degrade easily in concrete due to aggressive alkaline environment as they have a low alkali resistance [39].

Plastic fibres are divided into two groups according to their sizes; micro plastic fibres and macro plastic fibres which are subgroups of synthetic fibres. The micro plastic fibres have a diameter and a length ranging between 5 to 100 μm and 5-30 mm respectively while macro plastic fibres have an area and length ranging between 0.6 to 1.0 mm^2 and 30-60 mm respectively. However, micro fibres are generally more efficient in controlling cracks caused by plastic shrinkage of concrete due to excess evaporation rate at the first 24 hours of concrete placement [39]. Micro plastic fibres were also observed to improve mechanical properties, especially when fibres with higher ultimate tensile strengths (i.e. polypropylene fibres) were used [55]. On the other hand, macro plastic fibres were observed to be more efficient in control drying shrinkage cracks that are formed at the hardened phase. Although, steel mesh reinforcements were commonly used for this purpose, macro plastic fibres were being replace the steel because of lower cost and labour time, higher resistance to corrosion and more environmentally sustainable [39].

Compressive strengths of FRC's were observed to be higher compared to conventional concrete. Fibres included in concrete act as a bridge between the micro cracks and restrict the propagation and growth of these cracks. Therefore, more energy is required for the distribution of cracks to other locations within the concrete [4], [8], [56]. At the same time, some studies revealed contrary results which incorporation of plastic fibres resulted in reduction in the compressive strength of concrete. This could be due to many reasons such as cement and aggregate strength, adhesion characteristics and most importantly bundling of fibres. Bundling of fibres during inclusion, mixing and placement create weaker points which cause early cracks when loaded [9], [56], [57].

As stated before, the properties of fibre reinforced concrete changes based on many parameters such as dosage, dimension and characteristics of fibres, also adherence to the cement matrix and dispersion on fibres in matrix [50].

3.2 PET Fibre Reinforced Concrete

Currently, the sales of commodity products manufactured from virgin PET is unfortunately much more than the recycling of these post-consumer wastes. Therefore, recycling and incorporating these PET wastes into cement matrix as a fibre reinforcement is an alternative solution [56], [58]. In the literature, many laboratory experiments were carried out to incorporate large volumes of discarded PET waste in the form of aggregates of fibres as replacement or additional materials in concrete. PET waste commonly utilized in concrete applications as fine or coarse aggregate filler material for the production of light weight concrete. Moreover, PET waste incorporation on concrete applications as recycled PET fibres significantly improves crack resistance, tensile strength and ductility of concrete [59].

Incorporation of fibres in concrete dramatically decreases the workability of concrete mixes at fresh state, yet enhances the tensile strength and flexural strength of concrete composites on the hardened state [60]. The effect of recycled PET fibres on the mechanical properties of concrete was studied by many researchers, but still there are many contradictory views depending on characteristics of fibres incorporated. Generally, PET fibres were observed to improve tensile and flexural strength of concrete due to bridging effect of the fibres reduces crack openings, prevents propagation of cracks and enhances the post cracking residual strength of concrete [8]–[10], [57], [61]. The rupture of fibre, fibre/matrix debonding and pull-out of fibre from matrix are the energy absorbing mechanisms leading to the enhancement in the toughness (ability to absorb energy) of concrete [47] This improved behaviour is primarily depended on the quantity of fibres effectively crossing over the crack [60].

The influence of recycled PET fibres is still not understood yet because of many contradictory findings in the literature. However, few studies observed a decrease in the compressive strength of concrete with addition of fibres [6], [10], [41], [59], [62], some studied revealed an increase in the compressive strength associated with fibre addition [8], [9], [63]. Furthermore, some researchers observed insignificant alterations [4], [13], [64], whereas the reason for these variations in the findings can be attributed to characteristic and proper distribution of fibres in the matrix.

Plastic shrinkage resistance of recycled PET fibre reinforced concretes were rarely investigated in the literature. Borg et al. 2016 studied the effect of shredded plastic waste on the plastic shrinkage resistance of concrete. Deformed and longer fibres were observed to be more efficient in crack width reduction than straight and shorter fibres.

The properties of recycled PET fibre reinforced concrete depend on my properties, such as, the chemical and physical characteristics of fibres, dimensions, dosage of fibres and the adherence between the binder and fibres. Therefore, the performance of the RPFRC should be investigated thoroughly to comprehend the mechanical behaviour of this composite.

Chapter 4

METHODOLOGY AND EXPERIMENTAL PROCEDURE

4.1 Materials

Materials used in these study in order to experiment the effect of recycled PET fibres on the plastic shrinkage resistance and mechanical strength of concrete are listed below;

4.1.1 Cement

The type 1 ordinary Portland cement of 42.5 was procured from Cyprus Environmental Enterprises (CEE) limited which met the requirements of TS EN 197-1:2011 was used in the production of recycled PET fibre reinforced concrete. The physical and mechanical properties of the cement used are given in Table 1.

Table 1: Mechanical and physical properties of Portland cement

Composition	Amount
SiO_2 (%)	19.17
Al_2O_3 (%)	4.51
Fe_2O_3 (%)	3.24
CaO (%)	63.29
MgO (%)	1.99
SO_3 (%)	3.21
Na_2O Equivalent (%)	0.29
Loss on Ignition (%)	3.72
Insoluble Residue (%)	0.66
Chloride (%)	0.0128
Soluble Cr^{+6} (ppm)	27.90
Blaine Specific Area (cm^2/gr)	3700
Residue on 45 µm sieve (%)	2.50
Specific Gravity (gr/cm^3)	3.15
Compressive Strength at 2 days	28.80

4.1.2 Aggregates

Fine aggregates and coarse aggregates with maximum diameters of 5 mm and 10 mm respectively were obtained from crushed limestone were used in concrete mixes. Both aggregates have a density of 2.7 gr/cm^3 and the fineness modulus of fine aggregates were 3.09. The particles size distributions of the aggregates are given in Figure 5.

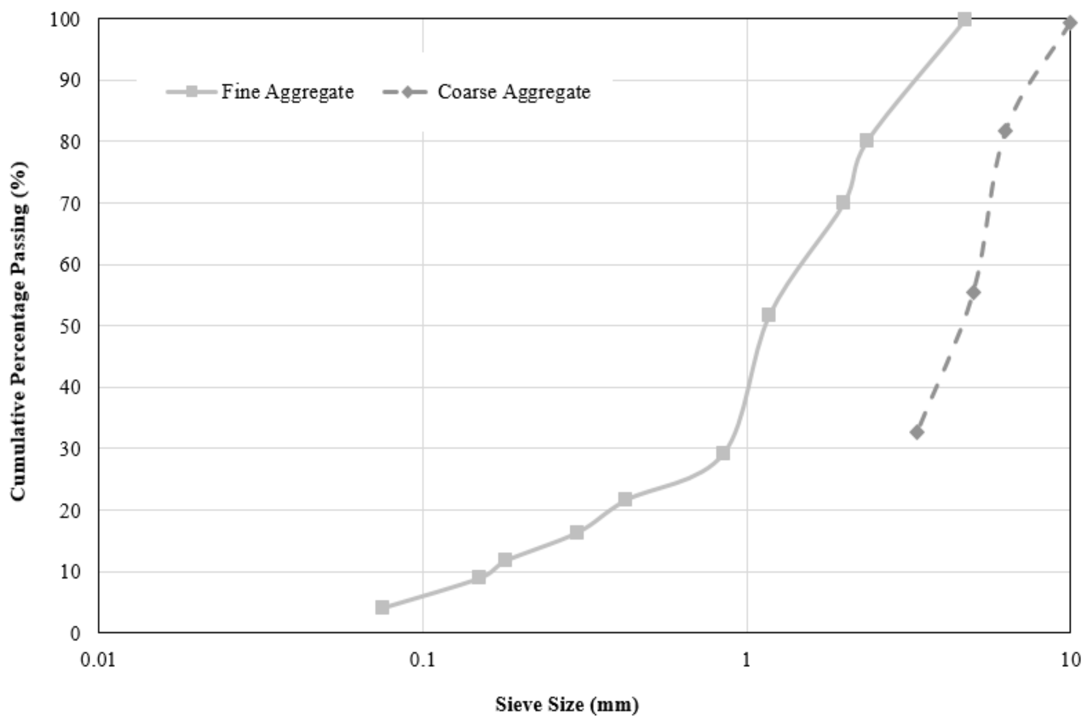


Figure 5: Particle size distribution of fine and coarse aggregates.

4.1.3 Water

Potable tab water was used for the preparation of all concrete mixes. Water was filled and kept in the containers in the ambient conditions until mixing.

4.1.4 Recycled PET Fibres

The recycled PET fibres were procured as 1200 mm monofilaments from a company in Turkey which produces a brush hair. The selected diameters for recycled fibres were 0.45 mm, 0.65 mm and 1.0 mm. The procured monofilaments with three different diameters were then cut into intended lengths of 20 mm and 30 mm by using hydraulic guillotine machine supplied by a local broom factory in North Cyprus. From discarded waste to fibre, the PET material passed through many steps. Firstly, the collected PET waste was washed, shredded and separated from unwanted contaminants. Then, these shredded flakes were melted into small PET chips to satisfy homogeneity. Treated and homogenized PET chips were after inserted into mechanical extruding machine and by the help of spooling device, the monofilaments were drawn out from the nozzle of the extruder in the any desired thicknesses. The cutting process of 0.45 mm, 0.65 mm and 1.0 mm diameter long monofilaments into fibres can be seen in Figure 6.

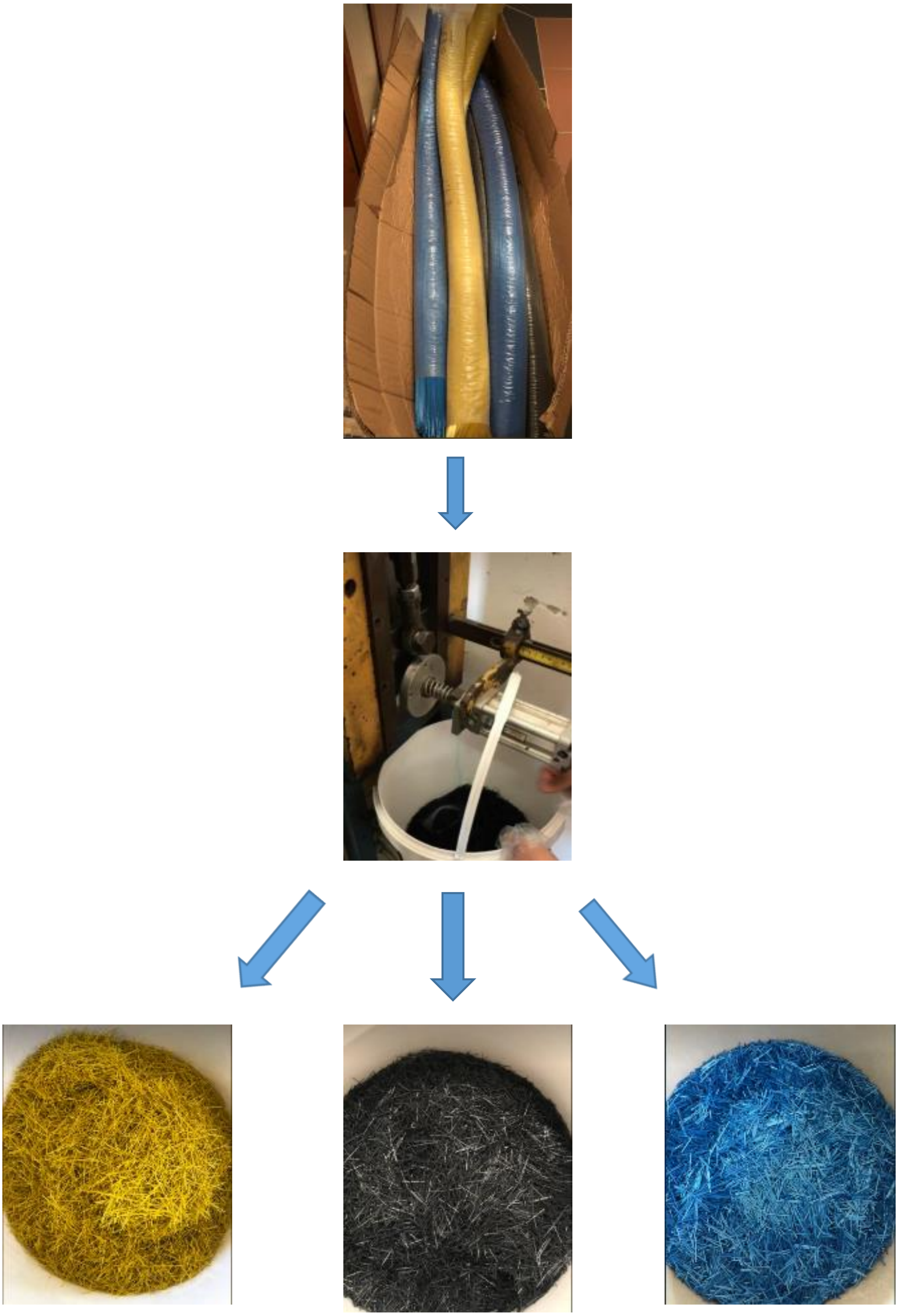


Figure 6: Cutting process of long monofilaments into small fibres.

4.2 Recycled PET FRC Sample Design & Preparation

Plain and PET fibre reinforced concrete specimens were mixed, placed and cured according to ASTM Standard C192/192M-16a, (2016). All constituents were weighed and then mixed using a conventional rotary pan mixer. Aggregates, cement and water added to mixer at the beginning and mixed for 30 seconds before fibres are added. Control concrete and recycled PET fibre reinforced concrete (RPFRC) specimens were prepared for analysis of fresh properties, mechanical strengths, plastic shrinkage resistance and impact resistance according to BRE [16] mix design procedure and the mix design formulation parameters are given in Table 2.

Table 2: Mix design parameters for concrete specimens.

Materials	Properties	Quantities
Cement	CEM I/42.5R	510 kg/m3
Water	Tap water at room temperature	250 kg/m3
Fine Aggregate	Crushed Limestone Dmax = 5mm	900 kg/m3
Coarse Aggregate	Crushed Limestone Dmax = 10mm	650 kg/m3
Fibre	Recycled PET fibres with diameters of 0.45mm, 0.65mm and 1.0mm, and lengths of 20mm and 30mm	Added at 0.5, 1.0, 1.5 and 2.0 vol% of plain concrete. (8.1-8.3 kg/m^3 fibre addition at 0.5%)

Although, recycled PET fibres have a detrimental effect on workability, the mix design was prepared to obtain the highest slump as possible for reference concrete samples, thus high quantity of fibres can be incorporated. Water to cement ratio (w/c) of 0.49 was provided for all mixes. Recycled PET monofilaments which were manufactured as brush hair, with various diameters (0.45, 0.65 and 1.0 mm) were procured from a broom company in Turkey. Fibres were then cut from the monofilaments into desired lengths of 20 mm and 30 mm and added into concrete mixes on a volume basis (see Figure 7). Aspect ratio of fibres mentioned in the study implies to length/diameter ratio of each fibre type. 0.45, 0.65, 1.0 mm fibres with 30 mm lengths have aspect ratio of 67, 46 and 30, while 20 mm length fibres have 44, 31 and 20 respectively. Fibre volume percentages were chosen to be 0.5%, 1.0%, 1.5% and 2.0%. Fibres were added gradually at the last stage of mixing to avoid bunching of fibres and non-uniform fibre distribution (see Figure 7). Vibrating table was applied to all samples to eliminate air bubbles and achieve a homogeneous mix. All casted specimens were cured at 23 ± 2°C and 95 ± 5% relative humidity until the day of testing.

Figure 7: Utilization of recycled PET fibres to concrete mix.

4.3 Experimental Procedure

4.3.1 Slump

Although the fresh state of concrete is temporary, its characteristic and condition indirectly affects the properties of hardened concrete. Workability is the primary property of fresh concrete which is defined as ease of placement without segregation. Therefore, slump tests were conducted prior to casting in order to see the effect of recycled PET fibres with various diameters and lengths on the slump of concrete at different volume percentages. The tests were carried out according to ASTM C143/C143M-20.

4.3.2 Compressive Strength

Compressive strength is one of the major criteria of evaluating the quality of concrete. Cube specimens with target strength of 40 MPa and dimensions of 150x150x150 mm were casted for evaluation of compressive strength as shown in

Figure 8(a). Four cubes for each sample were tested and average value was taken. Tests were carried out at a hydraulic compressive testing machine with a capacity of 3000 kN (Figure 8 (b)).

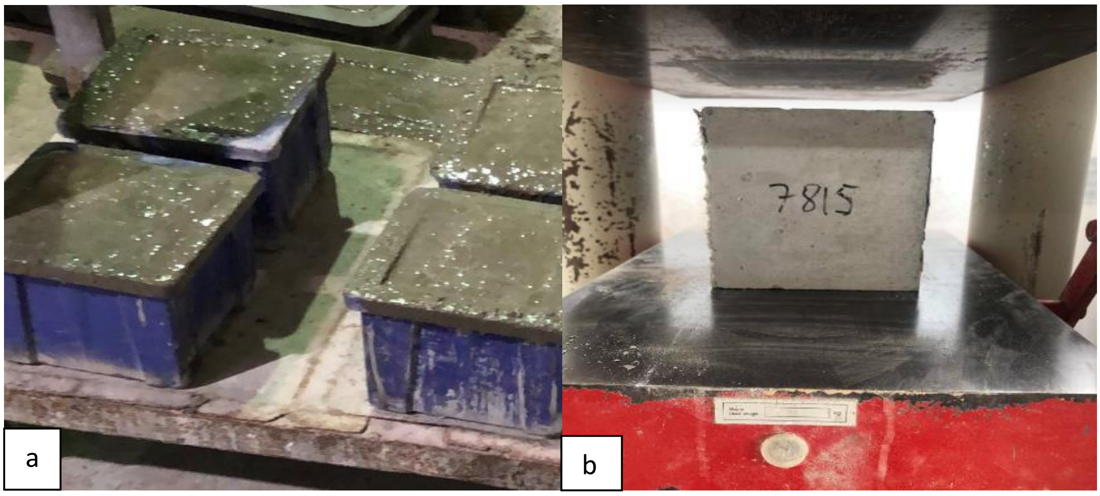


Figure 8: (a) Cube specimens, (b) Cube compressive strength testing.

4.3.3 Flexural Strength and Splitting Tensile Strength

Flexural and splitting tensile strength tests are methods of determining indirect tensile strength of concrete. Prismatic specimens (100x100x500 mm) and cylindrical specimens (100x200 mm) of control and recycled PET fibre reinforced concrete were casted for flexural strength and splitting tensile strength tests, respectively. Specimens were kept in a moist curing room at a controlled temperature and relative humidity for 28 days. On the day of testing, all specimens were removed from curing room and excess water was wiped from the surfaces. Dimensions and masses of all specimens were also measured prior to each testing. Moreover, each sample was visually inspected after failure and any unexpected crack pattern or failure mechanism was marked down. Flexural and splitting tensile strength tests were carried out at a hydraulic testing machine with a capacity of 200 kN and 3000 kN respectively (see Figure 9(a)-(b)).

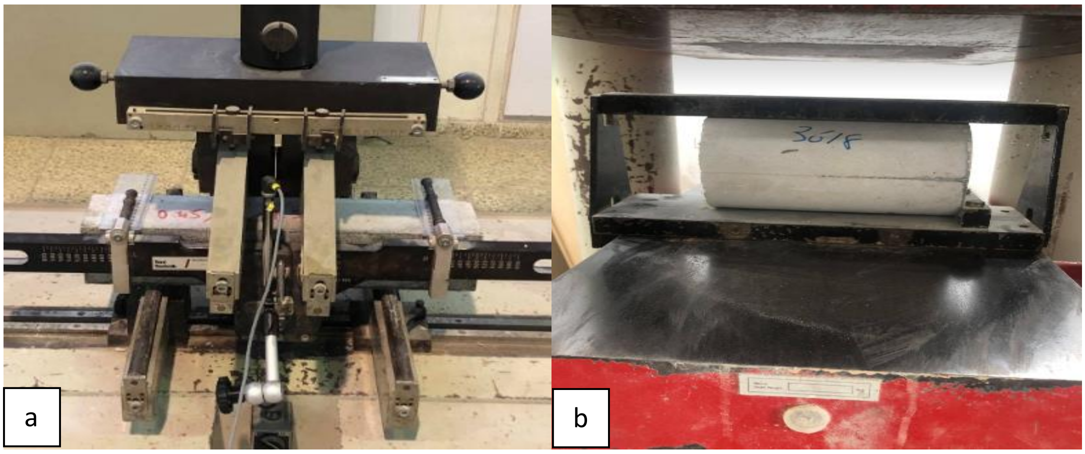


Figure 9: Testing equipment for (a) beam flexural strength, (b) cylinder splitting tensile strength.

4.3.4 Plastic Shrinkage

ASTM Standards C1579-13, (2013) was followed to evaluate plastic shrinkage resistance of recycled PET fibre reinforced concrete specimens. Environmental chamber containing the plastic shrinkage moulds installed with stress riser and internal restraints were prepared as shown in Figure 10 (a)-(b). Environmental chamber consisted of heaters and dehumidifiers to maintain temperature at 36 ± 3 °C and relative humidity at 30 ± 10%. Evaporation rates over 0.5 kg/m^2.h causes compressive strains which creates tensile strength sufficient to cause cracks in early stages [15]. In order to achieve an average evaporation rate of 1 kg/m^2.h and to validate the experiment, an industrial high velocity fan was located among heaters and moulds to provide 5 m/s wind speed.

Figure 10: (a) Plastic shrinkage mould with installed stress risers, (b) Filled plastic shrinkage and setting time moulds placed in environmental chamber, (c) Crack width measurement via optical hand-held microscope.

Plastic shrinkage tests were conducted for various fibre dimensions and volume fractions. For every PET-added concrete sample, a plain concrete sample was also prepared as a reference. Freshly prepared concrete was placed into the metal shrinkage moulds (see Figure 11). Hygrometer was installed 100 mm above moulds to monitor temperature and relative humidity continuously and a handheld anemometer was used to measure wind speed above specimens during tests. The setting time of both control and fibre-added specimens were regularly monitored using the procedures described in ASTM Standard C403/403M, (2008).

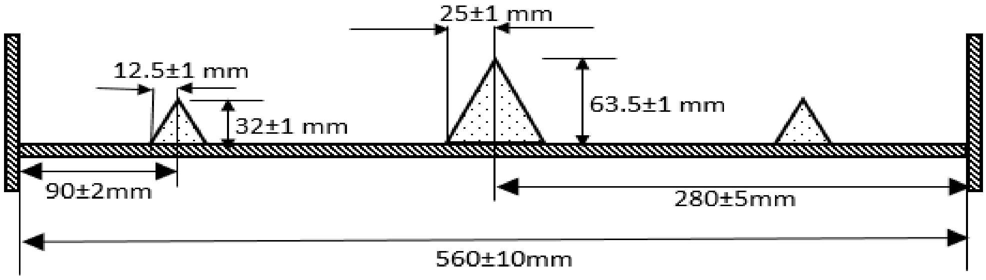


Figure 11: Stress riser and internal restraints geometry.

Heaters and fans were switched off when final setting of both control and RPFR concrete samples attained. Moulds were then covered with plastic sheets to prevent evaporation and kept at environmental conditions for other 8 ± 2 hours before crack width measurement. Optical handheld microscope (Figure 10 (c)) capable of measuring crack width to nearest 0.02 mm was used during analyses. Average crack width of each sample was determined by taking the average of 20 values along the crack line over stress riser and Crack Reduction Ratio (CRR) was calculated by using Eq. (1).

$$\mathrm{CRR} = 1 - \left[\frac{\text{Av.Crack Width of RPFRC}}{\text{Av.Crack Width of Control Concrete}} \times 100\%\right] \tag{1}$$

4.3.5 Impact Resistance

ACI Committee 544, (1988) report was followed for the determination of impact resistance of recycled PET fibre reinforced concrete. Drop weight impact test was performed in order to evaluate energy absorption capacity of PFRC specimens until a specific level of distress. Samples of concretes which were reinforced with 30mm long PET fibres were cast into cylindrical moulds (300x150 mm). The samples were then cut into four smaller cylindrical specimens with 63.5 ± 3 mm lengths to be adapted for testing equipment, using a table saw with diamond blade.

Test setup consists of a 4.54 kg compaction hammer which is released from a distance of 457 mm onto a steel ball. Steel ball was placed in a positing bracket on top of the specimen as shown in Figure 12. Compaction hammer was dropped repeatedly, and the number of blows required to cause the first visible crack and ultimate crack for each sample were recorded. Four positioning lugs were attached to the base plate at 4.76 mm distance from the circumference of specimens. Ultimate failure crack was defined as the point when concrete pieces were in contact with three of the four positioning lugs due to deformation of specimens. Finally, impact energy was calculated using equation given below, where; E is the impact energy (Nm), M is the mass of steel ball (kg), V is the velocity of drop hammer (calculated as 2.12 m/s) and N is the number of blows needed for ultimate crack [52].

$$E = \frac{1}{2} MV^2 N \quad (2)$$

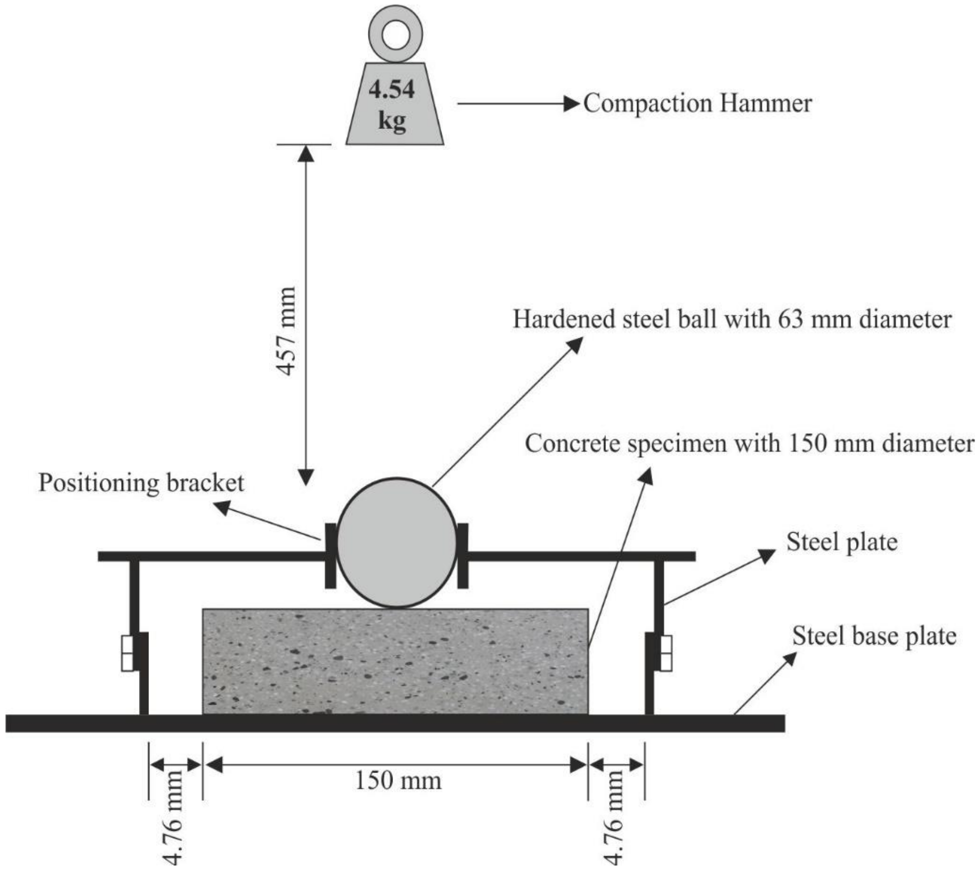


Figure 12: Schematic diagram of drop weight impact test apparatus.

4.3.6 Pull-out Resistance

The mechanical bond strength between cement paste and recycled PET fibre have a key role in controlling plastic shrinkage cracks in fibre reinforced concrete. Various diameters recycled PET fibres with lengths of 60 mm were selected for this test. Cube specimens with dimensions of 50 x 50 x 50 mm were prepared and 60 mm long fibres were placed into concrete where only 15 mm of the fibres were embedded. Last 30 mm part of fibres were tied up to form a circular hole for placing the hook at the tip of the weights. The experiment was adapted from JCI-SF 8 standard and the schematic diagram of the apparatus is shown in Figure 13. Loads were increased by 10gr at each time until complete pull-out of fibres from concrete. Diameter of PET fibres were 0.45, 0.65 and 1.00 mm while 8 samples were prepared for each one and the average was taken as a result.

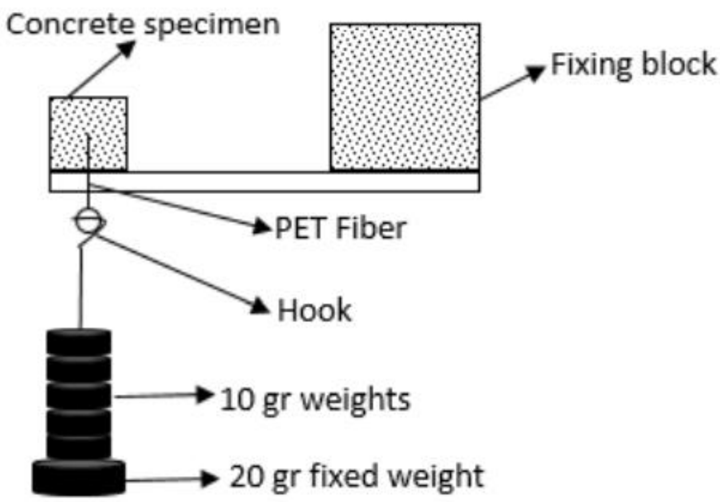


Figure 13: Schematic diagram of pull-out apparatus

4.3.7 Tests for superplasticizer added RPFRC mixes

The focus of this part of the experimental study was 0.45 mm diameter fibres with a 30 mm length as this fibre performed better than other recycled PET fibre types in the various tests carried out. In this part, superplasticizer was introduced into RPFRC mixes to enhance the volume of fibres incorporated into mixes. The aim is to keep equal workability via addition of superplasticizers to balance the loss of workability due to fibres. The compressive strength and plastic shrinkage resistance of RPFRC mixes were examined in this part. At the beginning, all constituents for each sample were arranged and weighed according to BRE mix design. ASTM Standard C192/192M-16a, 2016 was followed at each step (mixing, casting and curing) for preparation of all control and recycled PET fibre reinforced control samples. Water to cement ratio (w/c) of 0.49 and Polycarboxylate Ether superplasticizer with varying dosages were provided for all samples. Although, slump of cement based composite decreases with increasing fibre content, superplasticizer was included in order to achieve similar workability at different volume of PET fibre additions.

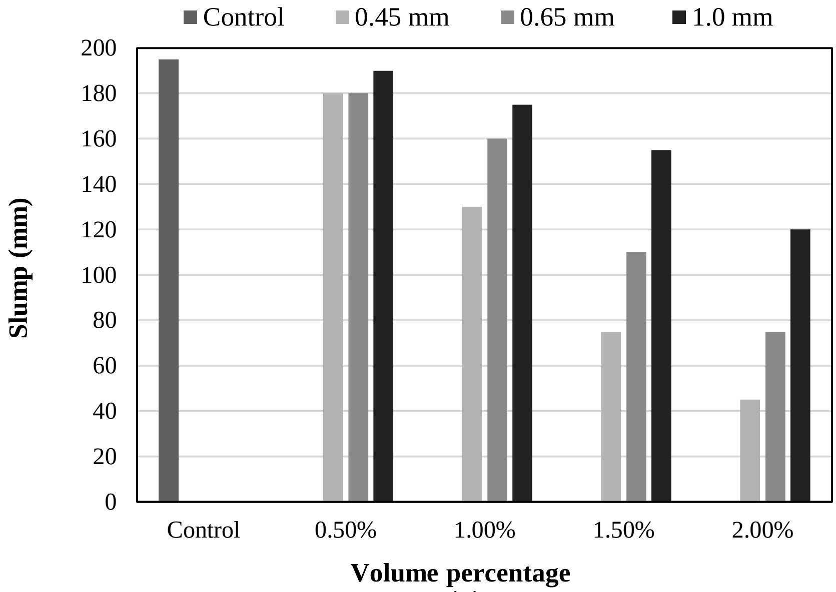
Chapter 5

RESULTS AND DISCUSSIONS

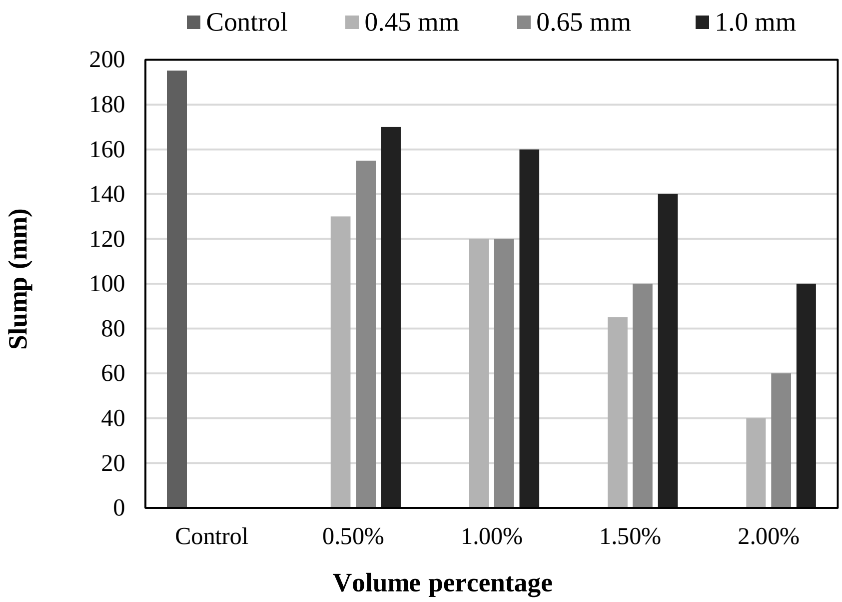
Results obtained from the experimental investigations are given below;

5.1 Slump

Figure 14 (a)-(b) present the workability of control and RPFRC samples incorporating 30mm and 20mm fibres respectively by using slump measurement results. It can be seen that the addition of recycled PET fibres has reduced the slump of the concrete in all conditions. This could be due to an increase in the surface area to be covered by cement matrix and inter-particle friction as a result of fibre addition [51]. The fibres are suspect to agglomerate and form bunches of fibres, which in turn, reduce the followability of concrete. Moreover, utilization of fibres prevents the flow of concrete matrix by causing a formation of network structure. This was an expected behaviour and this trend was commonly observed in various literature studies [9], [61]. Fibres with 30 mm lengths were observed to have minimal effect on slump up to 0.5% volume fraction, where further increase of fibre volume resulted in consistent decrease of slump. At 2.0% fibre fraction, reductions in slump were 76%, 61% and 38% for 0.45, 0.65 and 1.0 mm fibres with 30 mm lengths respectively. On the other hand, short fibres (20 mm) exhibited a sudden decrease from 0.5% to 2.0% and lower slump was obtained at all fibre fractions. At 2.0% fibre fraction, reductions in slump were 80%, 70% and 49% for 0.45, 0.65 and 1.0 mm fibres with 20 mm lengths respectively. The results also revealed that longer fibres exhibited higher slump values at all volume fractions. Nevertheless, for length comparison, longer fibres are expected to have a higher detrimental effect on the workability due to higher potential of entanglement. However, at a fixed total fibre volume, the number of 20 mm fibres is higher than that of 30 mm fibres, which increases potential fibre to fibre interactions and indirectly reduces the slump. Although fibres caused up to five times slump reduction compared to plain concrete, RPFRCs still provided sufficient workability and did not require excessive external vibration for compaction.



(a)



(b)

Figure 14: Slump test results for (a) 30 mm and (b) 20 mm RPFRC

5.2 Compressive Strength

The influence of fibre dimensions and fibre volume fractions on the compressive strength was investigated and the results are illustrated in Figure 15. It can be seen from results that 0.45 mm diameter fibres with 30 mm and 20 mm lengths enhanced compressive strength compared to that of control concrete up to 1.5% and 1.0% introduction of fibres respectively. The highest improvement of 14% compared to control concrete was achieved by 0.45 mm diameter and 30 mm length fibres, which has the highest aspect ratio amongst all available fibres. Fibres have an ability to restrict extension of cracks and alter crack direction thus delaying crack growing rate [33] and increased the energy required to cause failure. Furthermore, distributed PET fibres in the concrete mixture enhance homogeneity and reduces voids, which as a result, increases the cohesiveness of concrete. Results also revealed that 0.65 mm fibres exhibited an increase at 0.5% volume fraction, conversely further introduction of fibres in concrete resulted in a slight decrease in compressive strength. The compressive strength decreases in most cases with further addition of PET fibres which can be attributed to change of adhesion between fibres and cement paste. The insignificance of fibre addition on the compressive strength was previously mentioned in the literature [4], [69], [70]. Moreover, 1.0 mm fibres exhibited a slight decrease at all fibre contents and this slight reduction in compressive strength could be attributed to trapped air voids caused by fibre entanglement, which reduced the load-bearing area within the sample cross-section. This phenomenon was observed to be valid for all fibre types. Minor decrease in compressive strength with incorporation of PET fibres was previously encountered in previous studies [10], [71], [72]. The results are qualitatively contradicting with the study conducted by Fraternali et al., (2011). in terms of aspect ratio, in which the fibres with higher aspect ratios exhibited lower compressive strength values. This behaviour of recycled PET fibres depends on the geometry, dispersion, and the adherence to the cement matrix. The effect of fibre length on compressive strength was negligible except for 0.45 mm diameter fibres. However, the control concrete specimens were failed disastrously, the fibre incorporated specimens were failed with several minor cracks on the surface while the concrete specimens were still held together by the fibres after failure.

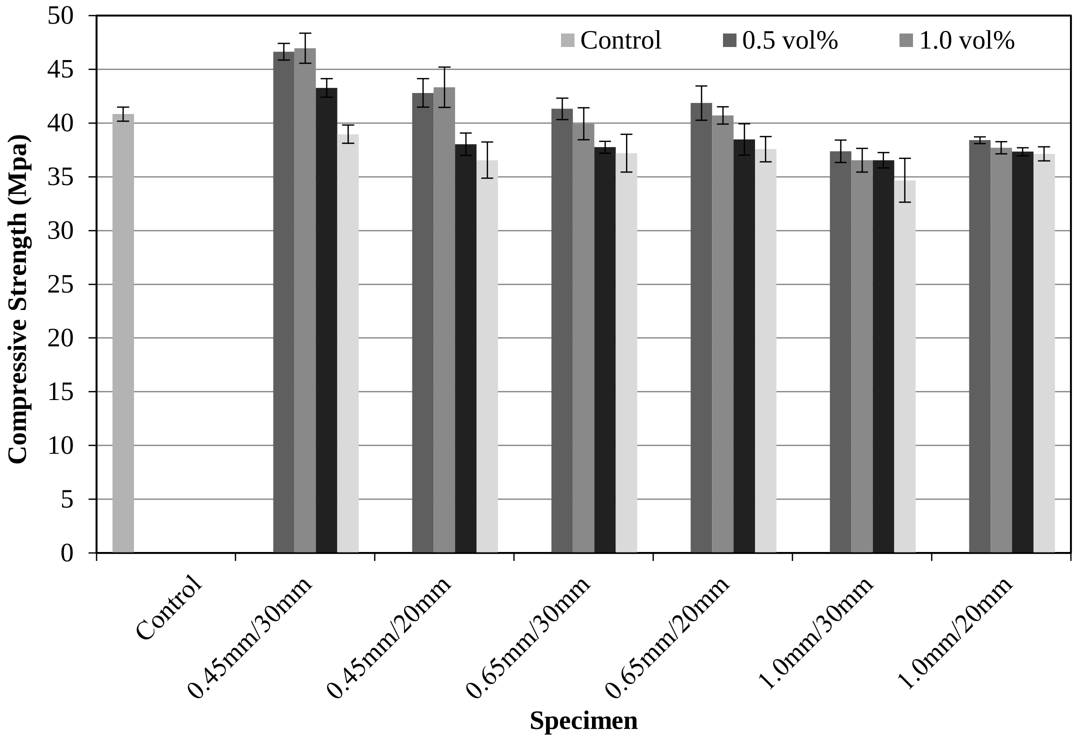


Figure 15: Influence of fibre dimensions and fibre volume fractions on compressive strength.

5.3 Flexural Strength and Splitting Tensile Strength

Figure 16 and Figure 19 represent results for flexural and splitting tensile strengths, respectively. According to the results, fibres with 0.45 mm diameter and 30 mm length exhibited the highest improvement in flexural strength up to a fibre content of 1.5%. By contrast at 2.0% volume fraction, flexural strength drastically decreased to a strength of concrete without fibres. The reason for this drastic decrease could be attributed to formation of fibre entanglement during mixing, as this characteristic is the main drawback of fibre reinforcements. For the rest of the fibres, moderate increase up to 10% was observed compared to control concrete at different dosage of fibre additions by virtue of the crack arresting mechanism of fibres. Although, the control specimen cracks and collapses instantly at the first crack without any deformation and prior warning. The failure progresses with bending without any instant collapse in the PET fibre introduced specimens. During concrete failure, the load is transferred to the plastic fibres, which in turn, prevent the spreading on cracks. When fibres with 1.0 mm diameter and 30 mm length were added at 1.5% and 2.0% fibre volume fractions, flexural strength decreased by 4% and 15% respectively. The highest improvement of 20% was attained by fibres with 0.45mm diameter and 30 mm length, which have the highest aspect ratio. Meanwhile, slight variations were observed for fibres with diameter of 1.0mm and lengths of 30 mm and 20 mm, which have the lowest aspect ratios.

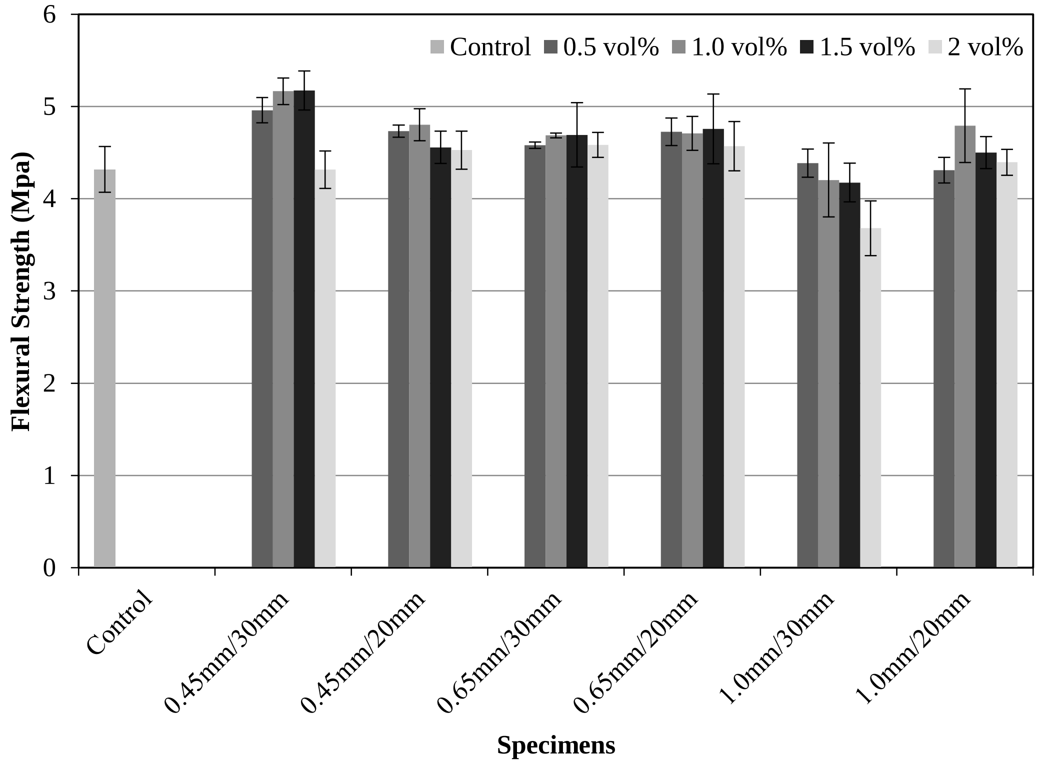


Figure 16: Influence of fibre dimensions and fibre volume fractions on flexural strength.

Like flexural strength, splitting tensile strength was also improved by 20% compared to concrete without fibres with the inclusion of 0.45 mm diameter and 30 mm length fibres at 0.5% volume fraction. This was followed by a slight decrease in progress up to 1.5% volume fraction. On the other hand, at 2.0% volume fraction, the tensile strength declined by 9%. Apart from the fibres with 1.0 mm diameter and 20 mm length, increments in splitting tensile strengths were observed up to 1.0% fibre fraction. However, further addition of fibres led to similar or even slightly lower values compared to control concrete. This trend is qualitatively coherent with a similar study in the literature [33]. The figure 17 shows the correlation between the compressive strength and flexural strength of 0.45mm diameter PET fibre incorporated concretes. The graph highlights a direct relationship for 30 mm fibres, which means by increasing compressive strength, the rate of gaining in flexural strength increases. The established R^2 value of 0.91 indicates a high linear correlation between the two variables. On the other hand, inverse relationship was observed for 20 mm fibres while the established R^2 value of 0.60 indicates a very weak relationship between the two variables. This inverse relationship between two different fibre lengths could be attributed to the influence of aspect ratio of fibres on the bonding strength of concrete as explained before in this section.

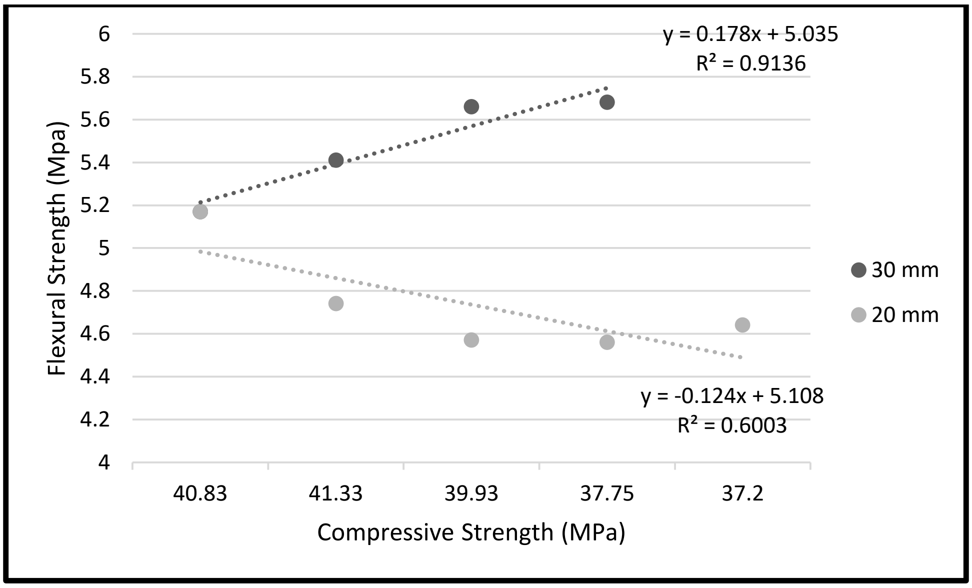


Figure 17: Relationship between Compressive Strength and Flexural Strength

The results also revealed that splitting tensile strengths of RPFRC specimens decreased with respect to increase in fibre volume fractions. As in flexural strength, fibres with higher aspect ratios were seen to perform better than fibres with lower aspect ratios, due to greater crack arrest ability. The reason for reduced flexural and splitting tensile strengths could be the entanglement of fibres that are creating air voids which result in stress concentrations within the samples. Moreover, the smooth surface of recycled PET fibres creates poor bonding between cement matrix and fibres, which leads to formation of voids and micro cracks resulting in slightly poorer strength characteristics [51]. Any potential improvement of flexural strength and splitting tensile strength due to the sewing effect of fibres could be dominated by the reduction of strength due to aforementioned air voids. Concrete without fibres instantly split once the specimen cracked, while PET fibre reinforced concrete specimens exhibited little deformations without splitting (see Figure 18). This represents that the fibre concrete has the ability to absorb energy in the post cracking phase. The flexural and splitting tensile strengths were expected to increase due to the ability of fibres to carry applied loads through interfacial bonds, which would prevent the propagation and sudden failure of concrete [12]. However other variables such as fibre geometry, consolidation and bonding strength between fibre surface and cement paste could have an opposite effect on the results. Furthermore, increasing the fibre volume fraction beyond a point increases the interaction between fibres, which possibly reduces the adhesion between fibres and cement paste. Nevertheless, the fibre length of 0.45 mm fibres had a visible effect on the mechanical properties, the effect of length for other fibre diameters was not significant.

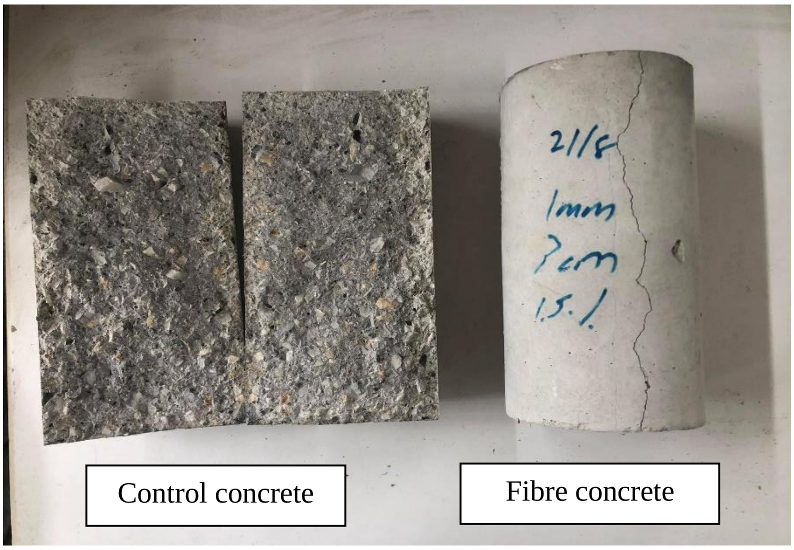


Figure 18: Failure mode of specimens during splitting tensile strength.

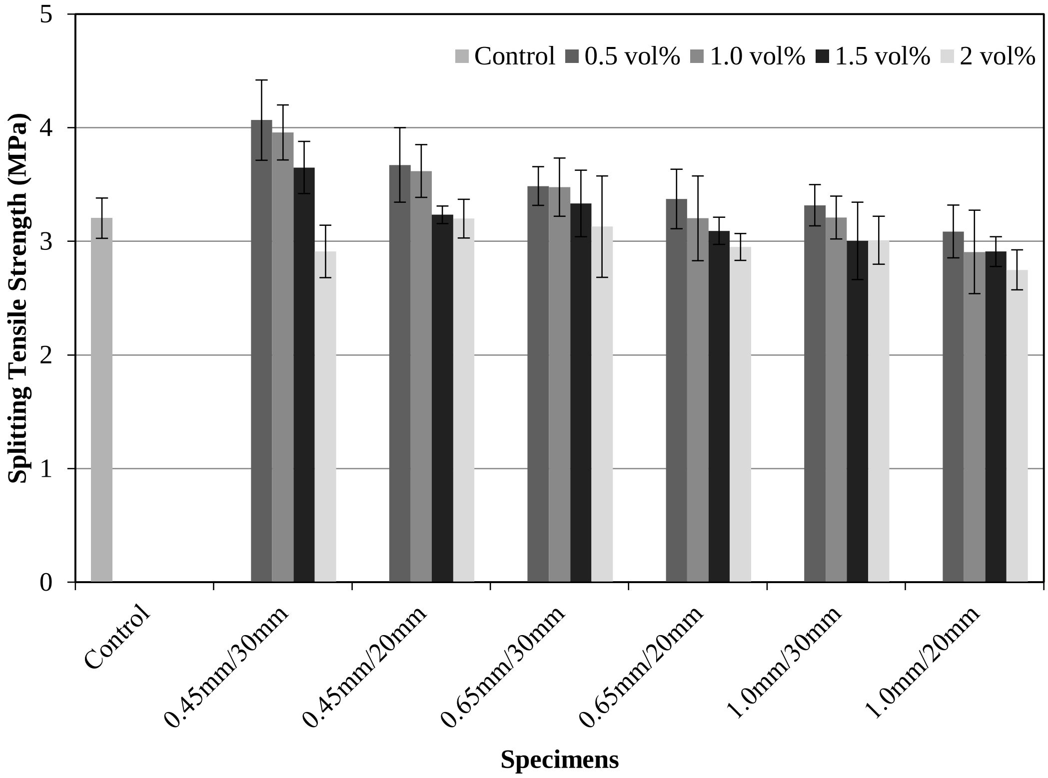


Figure 19: Influence of fibre dimensions and fibre volume fractions on splitting tensile strength.

5.4 Plastic Shrinkage Resistance

Plastic shrinkage resistance of the samples has been investigated in accordance to ASTM Standards C1579-13, (2013). Crack widths of control and RPFRC samples were measured using a hand-held optical microscope. Figure 21 shows the relationship between volume percentages and crack reduction ratios for fibres with varying diameters and lengths. With reference to the effects of fibre length, longer fibres showed higher performance than short fibres at all fibre fractions. Poor performance of shorter fibres was attributed to poorer bonding of fibres with the cement matrix, due to lower surface area per single fibre. In general, fibres with higher aspect ratios (l/d) performed better in the reduction of plastic shrinkage cracks because of greater bond with cement matrix that enhances the energy absorbed by sewing effect of fibres. Moreover, increasing volume of fibres was observed to increase crack reduction ratios for all fibre types. Even at 0.5% volume fraction, 0.45 mm, 0.65mm and 1.0 mm fibres with 30 mm lengths reduced crack widths by 68%, 65% and 44% respectively. Besides, fibres with 0.45 mm and 0.65 mm diameters and 30 mm lengths were found to reduce crack widths by roughly 100% at 2.0% fibre addition compared to conventional concrete. Shorter fibres with diameters of 0.45 mm, 0.65 mm and 1.0 mm at 1.5% fibre fraction reduced crack widths by 75%, 75% and 62% respectively. This behaviour could be due to the bridging effect of PET fibres caused by a mechanism of load transfer from cement matrix to fibres. Figure 20 illustrates the crack paths formed upon stress risers for concrete specimens with and without fibres during plastic shrinkage resistance tests. The results were qualitatively coherent with previous investigations carried out by Borg et al., (2016) and J. H. J. Kim et al., (2008) with reference to fibre volume fraction and fibre aspect ratio. However, various literature studies revealed that deformed PET fibres performed better than straight and smooth fibres due to higher mechanical bond strength, it was also mentioned that once the fraction of fibre volume exceeds 0.5%, an adequate number of fibres are included to control cracks due to plastic shrinkage, thus the fibre geometry had no further effect.

Figure 20: Failure mode of specimens during plastic shrinkage resistance test.

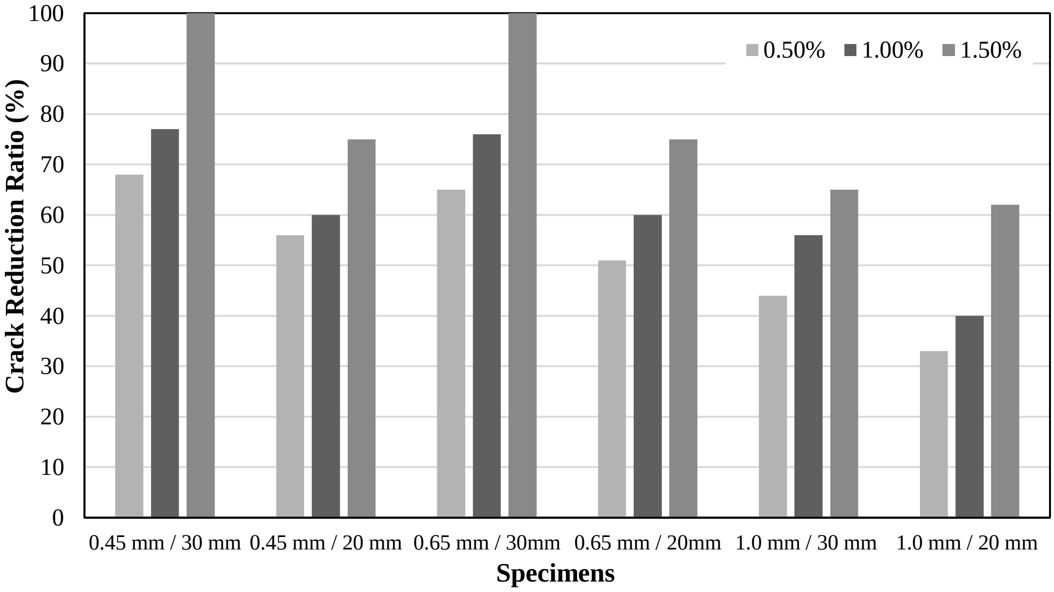


Figure 21: Influence of fibre dimensions and fibre volume fraction on the Crack Reduction Ratios.

5.5 Impact Resistance

Average number of blows required for ultimate crack of 150 mm x 63.5 mm specimens gathered from drop-weight impact test to determine the impact resistance of RPFRC specimens are shown in Table 3. Although there was no apparent effect of fibre addition on impact resistance to the first crack of concrete, their influence on impact resistance to the ultimate crack was found to be significant. Different fibre types were mentioned in the literature that have a positive effect in the impact resistance to initial crack of concrete unlike PET fibres. Nevertheless, these fibres observed to have less improvements on the ultimate crack resistance than PET fibres. Figure 22 clearly presents that at all fibre diameters, increasing fibre contents enhance impact energy (E), especially at over 1.0% fibre addition. Dashed line represents the impact energy calculated with regards to number of blows for control concrete. At 2.0% fibre addition, 0.45 mm, 0.65 mm and 1.0 mm fibres improved impact energy by 10, 5.7 and 4.5 times compared to control concrete respectively. Influence of fibres on impact energy increased with respect to increase in aspect ratio. Increasing fibre length results in either more uniform cracks or higher number of cracks. Therefore, for the same length fibres, decreasing fibre diameter increases the energy absorbed. This phenomenon was attributed to the bridging effect of fibres on concrete, while at an equal fibre volume, higher aspect ratio represents larger bonding surface area between fibres and cement paste.

Several micro-cracks were developed across RPFRC specimens instead of a single macro-crack and thus higher surface energy was dissipated [73]. Figure 23 shows crack patterns after ultimate failure of control and 0.45 mm, 2% fibre added concrete specimens subjected to drop-weight impact test. While control specimens were broken down and split into two pieces, PET fibre reinforced concrete specimens were exposed to external cracks without disintegration. A clear anchorage of recycled PET fibres was apparent in specimens with fibres [74]. Even at the ultimate failure, PET fibres were observed to keep lumps of concrete together and this characteristic of concrete prevents sudden collapse. Therefore, utilization of PET fibres as reinforcements in concrete enhanced ductility of concrete specimens by providing better resistance against deformations induced by impact loads and shocks.

Table 3: Number of blows required for ultimate failure.

Sample	Control	0.45 mm				0.65 mm				1.0 mm			
Vol %	0	0.5	1.0	1.5	2.0	0.5	1.0	1.5	2.0	0.5	1.0	1.5	2.0
No. of blows	32	70	112	168	327	58	72	116	182	45	49	102	145

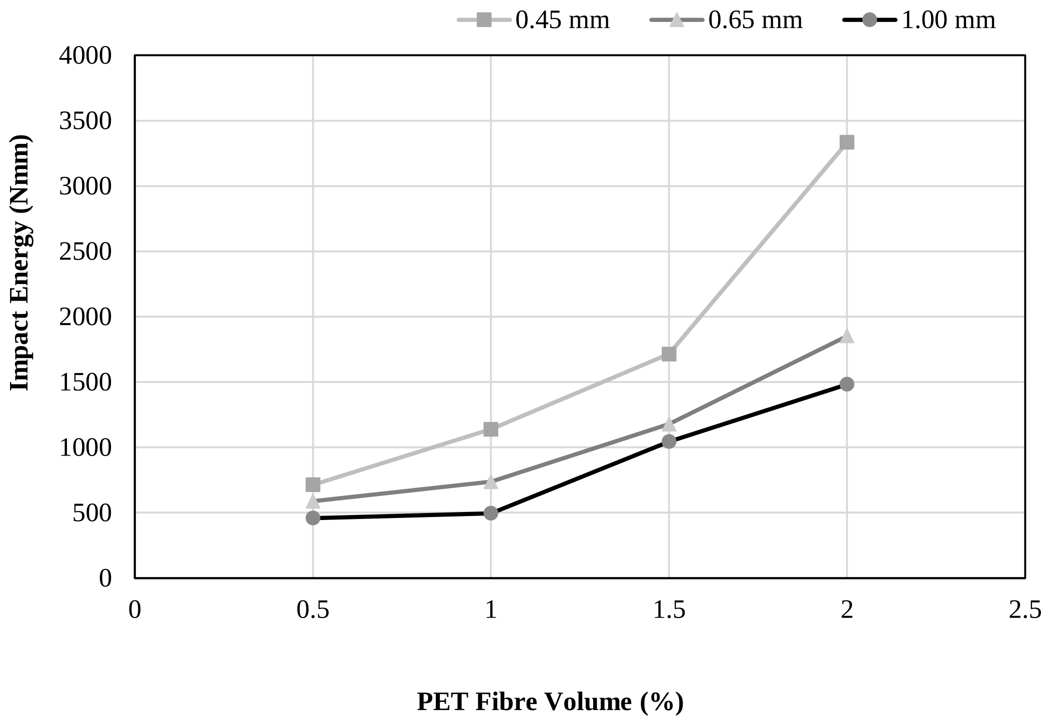


Figure 22: Influence of fibre diameter and fibre volume fraction on the impact energy of concrete.

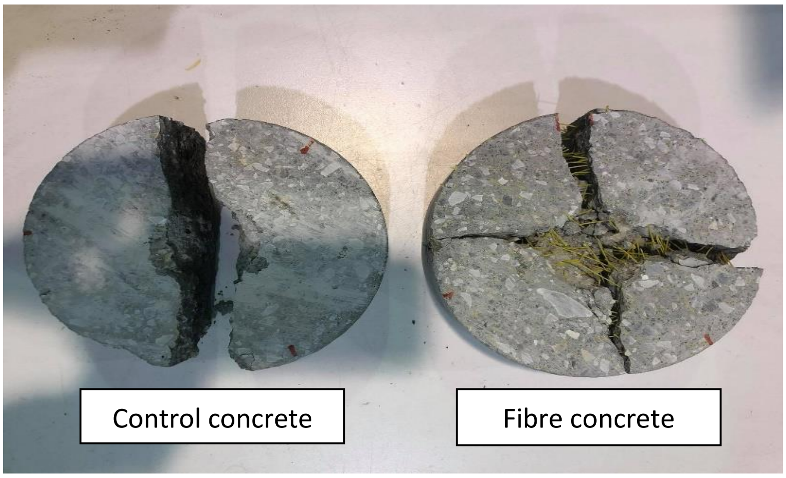


Figure 23: Failure mode of specimens during impact resistance test.

5.6 Pull-out Resistance

Manual pull-out resistance measuring apparatus (Fig.4) was designed and prepared for investigation of pull-out resistance of various diameter recycled PET fibres. Maximum mechanical bond strength of each fibre was calculated by using modified version of the Eq. (2) used in study by Kim et al., 2008. The results obtained are given in Table 4. According to results, 1.0 mm fibres which own largest diameter performed better 0.45 mm and 0.65 mm recycled PET fibres. This behaviour could be attributed to larger bonding area between fibre and cement paste causing higher load transfer. All aside, individual pull-out strength of fibre does not reflect the performance when applied in larger volumetric ratios. When fibres added in volumetric ratios, larger amounts of smaller diameter fibres are added compared to larger diameter fibres that causes differences in total bonding strength and load transfer.

$$\tau_{max} = \frac{P_{max}}{2(b+h)l} \rightarrow \tau_{max} = \frac{P_{max}}{2\pi r l} \quad (2)$$

where; P_{max} is a maximum pull-out load, r is the radius if fibre and l is the embedded length of fibre.

Table 4: Pull-out resistance test results.

Fibre Diameter (mm)	**Pull-out Strength (MPa)**
0.45	0.38
0.65	0.44
1.0	0.53

Figure 24: Pull-out resistance test apparatus.

The inverse relationship originates from the distinct effect of different diameter recycled PET fibres on the pull-out strength and impact resistance of concrete which can be seen in Figure 25. A plot illustrates the relationship between two properties at different volume fractions. A large R^2 value of 0.99 for 0.5% volume fraction indicates a very strong inverse correlation between two variables. However, R^2 values get smaller by increasing volume fraction, all R^2 values for all volume fractions indicates a strong inverse relationship between two variables. This strong correlation could be attributed to increased number of fibre inclusion with lower fibre diameters. The decrease in R^2 value by the increase in volume fraction could be due to the influence of other factors such as entanglement and segregation dominating the effect of fibres at higher volume fractions.

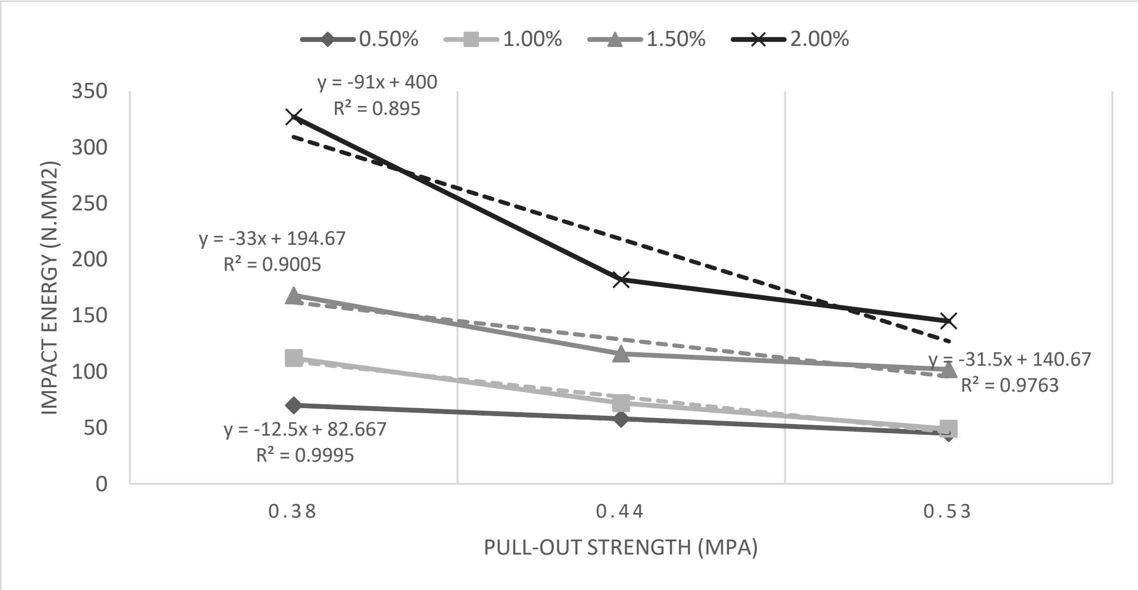


Figure 25: Relationship between pull-out strength and impact strength of different diameter fibres.

5.7 Test results for superplasticizer added RPFRC mixes

Table 5 below represent the slump values observed for mixes prepared without and with superplasticizer respectively. It can be seen that addition of 0.45 mm diameter and 30 mm length recycled PET fibres had an adverse effect on workability. The reason for this event can be attributed to increasing number of fibres increases surface of area required to be covered by cement matrix [51]. This behaviour of various types was observed in various literature studies [9], [61]. For specimens without superplasticizers, 11% reduction in slump was investigated at 0.5% fibre addition, however this reduction was continued with increasing fibre content while 90% slump reduction and balling was observed at 2.5% fibre addition. As fibre volume increases, potential for fibre entanglement and fibre to fibre interactions increases which also result in loss of slump. Therefore, experiments were repeated with various amounts of superplasticizer at each fibre volume addition until achieving similar slump value (±10mm) with reference concrete.

Table 5: Slump test results for RPFRC mixes with and without SP.

Fibre Vol. (%)	**Slump (mm)**
0.0	180
0.5	160
1.0	130
1.5	80
2.0	50
2.5	20

Superplasticizer (%)	**Fibre Vol. (%)**	**Slump (mm)**
0.00	0.0	180
0.00	0.5	170
0.10	1.0	190
0.15	1.5	170
0.35	2.0	170
0.35	2.5	170

5.7.1 Compressive Strength

Figure 26 illustrates the values observed for compressive strength tests for both specimens with and without superplasticizer. Results revealed that, as volume of fibres increases, compressive strength decreases for both specimens. However, for specimens with superplasticizers, decrease of compressive strength at 0.5% fibre addition was not negligible while rapid decrease of 15% was observed at 1.0% fibre addition. Furthermore, almost similar results were observed after that point up to 2.5% recycled PET fibre addition. The main reason for decrease in compressive strength in fibre utilized concrete composites was trapped air voids formed due to entanglement of fibres. For specimens without superplasticizer, there was no change observed up to 1.0% fibre addition compared to control concrete whereas 18% decrease was occurred between 1.0% and 2.0%. However, expectation was improved compressive strength with an inclusion of superplasticizer due to enhanced capability of compaction to bring out denser concrete. Addition of superplasticizer found to have detrimental effect on compressive strength when compared with control concrete without superplasticizer and fibres. Moreover, dosage of superplasticizer found to have no negligible effect on strength between 0.1% and 0.35%. Incompatibility of cementitious material and superplasticizer causes delays in setting time of concrete which results in reduction of strength and increase in porosity. Furthermore, 0.5% superplasticizer addition might be the optimum amount for this mixture. According to experiments performed, even at 2.5% fibre addition, closer values to target compressive strength of 40 MPa were achieved. Results are also consistent with the study conducted by Chu, 2019 [75].

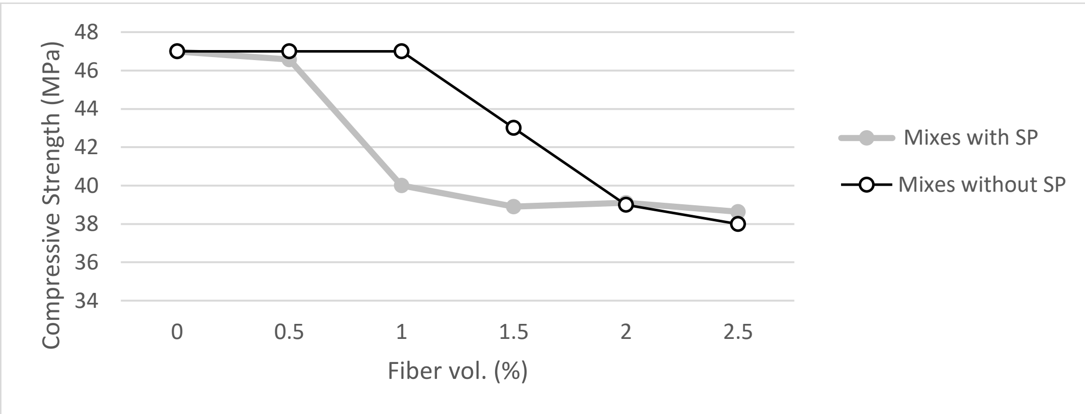


Figure 26: Compressive strength results of RPFRC mixes with and without SP.

5.7.2 Plastic Shrinkage Resistance

The introduction of various types of fibres as reinforcements in concrete applications was increased in recent years. Recycled fibres with different lengths, diameters and characteristics were used in literature in order to enhance tensile properties of concrete. Fibres generally added into concrete as volumetric fraction of concrete constituents. Fibres in concrete act as a bridge between cracks, thus preventing the propagation and reducing the size of cracks. Hence, more durable and shrinkage crack resistant concretes can be achieved. On the other hand, fibres have unfavourable effect (reduction) on slump which limit its addition amount. Reduced slump causes difficulties during placing of concrete into formworks, however slump of fresh concrete can be increased by addition of superplasticizers. Although the effect of recycled fibres on compressive and tensile strengths is not significant, fibres are very effective in preventing spreading and development of cracks [58]. Cracks occurred due to plastic shrinkage is one the main cause of decreasing service-life performance of concrete. There are many factors effecting the characteristics and origin of cracks such as span length and thickness, casting temperature (during placement), evaporation rate and humidity (Kim et al., 2008). Although concrete surfaces do not expose to plastic shrinkage cracks if not restrained, concrete surfaces are generally restrained with foundation or reinforcements. Tensile stresses being formed in restrained cement-based composites and cracks occur when the tensile strength of concrete is become less than tensile stresses occur due to plastic shrinkage. Recycled PET fibres dispersed randomly in cement based composites can be a solution of controlling cracks. These fibres create sewing effect by bridging between the magnitude of crack, thus limit the propagation and development of cracks.

Results obtained from plastic shrinkage resistance experiments of specimens with and without superplasticizer are given below in Figure 27. Hand held optical microscope was used to measure crack widths along the crack line of each specimen and crack reduction ratios were calculated. According to values observed, it can be clearly seen that as volume of recycled PET fibres introduced increase, crack reduction ratio (CRR) increases for both specimens. Specimens with and without superplasticizers succeeded in recovering all cracks at 2.0% and 1.5% fibre volume additions respectively. The reason of slower improvements for superplasticizer added samples can be attributed to increased setting time of mixes because of increased water content for hydration which can cause increments in porosity. Due to sewing effect, recycled PET fibres act as a bridge at the middle of cracks thus prevent propagation of minor cracks. Moreover, load transfer from cement matrix to fibres increases as fibre volume increases. In the study by Borg et al., 2016, similar trend was observed with shredded PET bottles. The compatibility of superplasticizer and cementitious material could also be the another reason of slower improvements in crack reduction ratios.

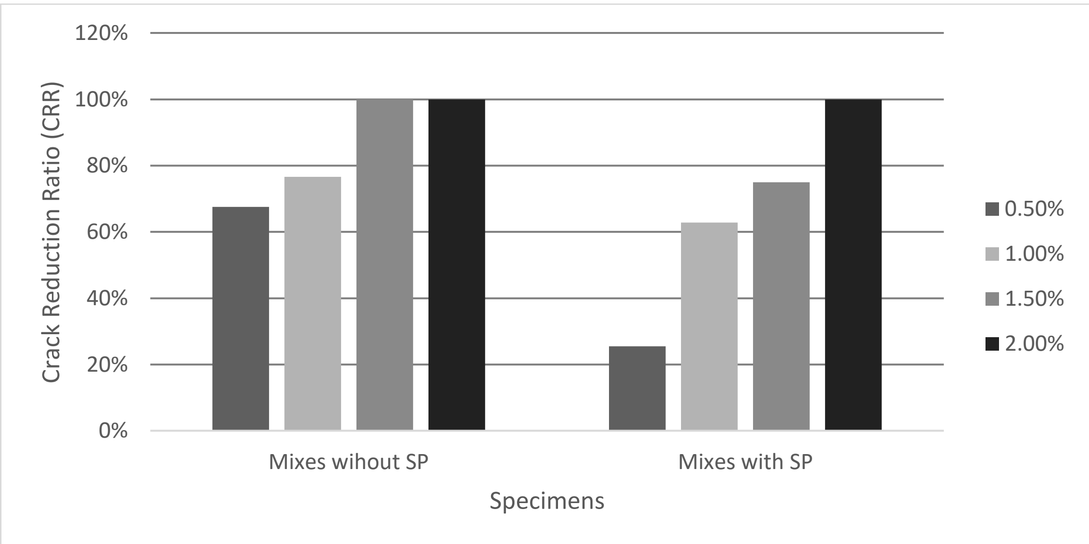


Figure 27: Plastic shrinkage resistance results of RPFRC mixes with and without SP.

Chapter 6

CONCLUSION

In this study, a comprehensive and comparative laboratory analyses were performed in order to investigate the effect of recycled PET fibres of different geometries on mechanical properties of concrete. Fibres with 0.45mm, 0.65mm, and 1.0 mm diameters and lengths of 20mm and 30 mm were incorporated into concrete at 0.5%, 1.0%, 1.5% and 2.0% in volume basis. PET added and control concrete specimens were prepared to investigate the behaviour of recycled PET fibre reinforced concrete compared to conventional concrete during compression, flexural and splitting tensile strength tests and plastic shrinkage and impact resistance tests. The environmental advantage of effective utilization of this non-biodegradable material is another preliminary motivation for the present study. The following conclusions are drawn based on results presented above.

- Slump cone test results revealed that for all diameter fibres, reduction in consistency of fresh concrete samples were observed with respect to increase in the volume fraction. Up to 76% and 80% reductions in slump were observed for 30 mm and 20 mm length fibres respectively. This was an expected behaviour due to increased surface area and inter particle friction due to the addition of fibres. Shorter fibres had more significant effect on reducing slump than longer fibres.
- Addition of PET fibres with diameters of 0.45 mm and 0.65 mm typically exhibited around 14.5% higher compressive strength compared to control concrete up to 1.0% volume fractions. However, further introduction of those

fibres resulted in reduction of compressive strength. On the other hand, 1.0 mm fibres exhibited a decrease at all fibre volume fractions. The highest reduction of 15% was observed at 2.0% fibre addition.

- Incorporation of PET fibres generally does not have any detrimental effect on flexural strength up to 1.5% and on splitting tensile strength up to 1.0% volume fractions. Results also brought out that, at higher fibre dosages, the bridging effect of fibres was hindered by formation of air voids due to entanglement. Maximum improvements in flexural and splitting tensile strengths were 10% and 27% which were obtained by 0.45 mm diameter fibres with 30 mm lengths.
- The addition of PET fibres improved the resistance of concrete against plastic shrinkage cracking substantially up to 1.5% volume fraction. Reduction in crack widths between 62-100% with reference to control concrete was achieved by all fibre types.
- Even though PET fibres had no distinct influence on impact resistance to the first crack, excellent improvements of the impact energies (up to 4.5-10 times compared to control concrete) was achieved by all types of fibres.
- Volume fraction of 2.5% was achieved by 0.45 mm diameter and 30 mm length PET fibres without any detrimental effect on the structure of mixture and compressive strength by inclusion of superplasticiser in concrete constituents. Slower development in the crack resistance of superplasticizer added could be attributed to the incompatibility superplasticizer with cementitious matrix.
- Fibres with larger diameters were found to have greater pull-out strengths than thinner fibres, but this does not reflect the total load capacity of fibres in the concrete due to variations in the number of fibres added for each fibre type.

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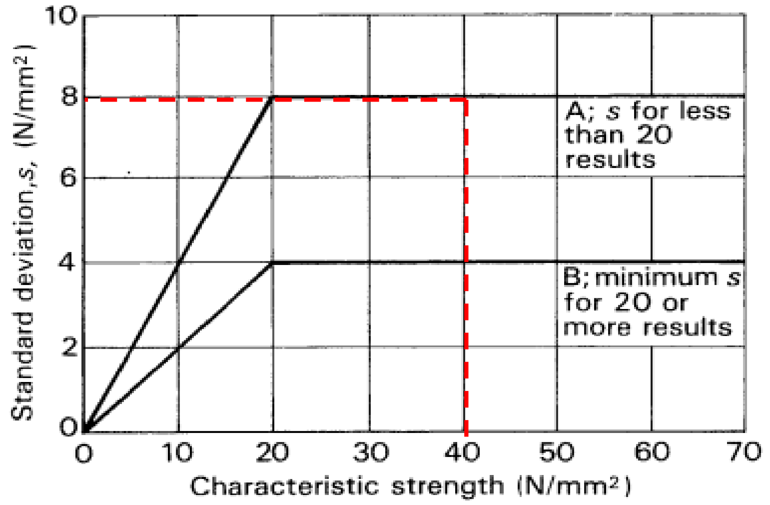
APPENDIX

MIX DESIGN

Stage	Item		Reference or Calculation	Values			
1	1.1	Characteristic Strength	Specified	**40**	N/mm^2 at	**28**	days
					Proportion defective:	**10**	%
	1.2	Standard Deviation	Fig 3	**8**	N/mm2		
	1.3	Margin	C1	(k= 1.28)	1.28 x 8 =	**10.24**	N/mm^2
	1.4	Target Mean Strength	C2		40 + 10.24 =	**50.24**	N/mm^2
	1.5	Cement Strength Class	Specified	**42.5**			
	1.6	Aggregate type: coarse		**Crushed**			
		Aggregate type: fine		**Crushed**			
	1.7	Free water/cement ratio	Table 2, Fig 4	0.49	Use the lower value	**0.49**	
	1.8	Maximum free-water / cement	Specified				
2	2.1	Slump or Vebe Time	Specified	Slump	**60-180 mm**		
	2.2	Maximum Aggregate Size	Specified			**10**	mm
	2.3	Free-water content	Table 3			**250**	kg/m^3
3	3.1	Cement Content	C3		250 / 0.49 =	510	kg/m^3
	3.2	Maximum Cement content	Specified	-	kg/m^3		
	3.3	Minimum Cement Content	Specified	-	kg/m^3		
			use 3.1 if ≤ 3.2			**510**	kg/m^3
			use 3.3 if > 3.1				
	3.4	Modified free-water/cement ratio				-	
4	4.1	Relative density of aggregate				**2.64**	known
	4.2	Concrete Density		Figure 5		**2310**	kg/m^3
	4.3	Total Aggregate Content	C4		2310 - 510 -250 =	**1550**	kg/m^3
5	5.1	Grading of Fine Aggregate	Percentage Passing 600μm sieve			**29**	%
	5.2	Proportion of Fine Aggregate	Fig 6			**58**	%
	5.3	Fine Aggregate content	C5		1550 x 0.58 =	**899**	kg/m^3
	5.4	Coarse Aggregate Content			1550 - 922 =	**651**	kg/m^3

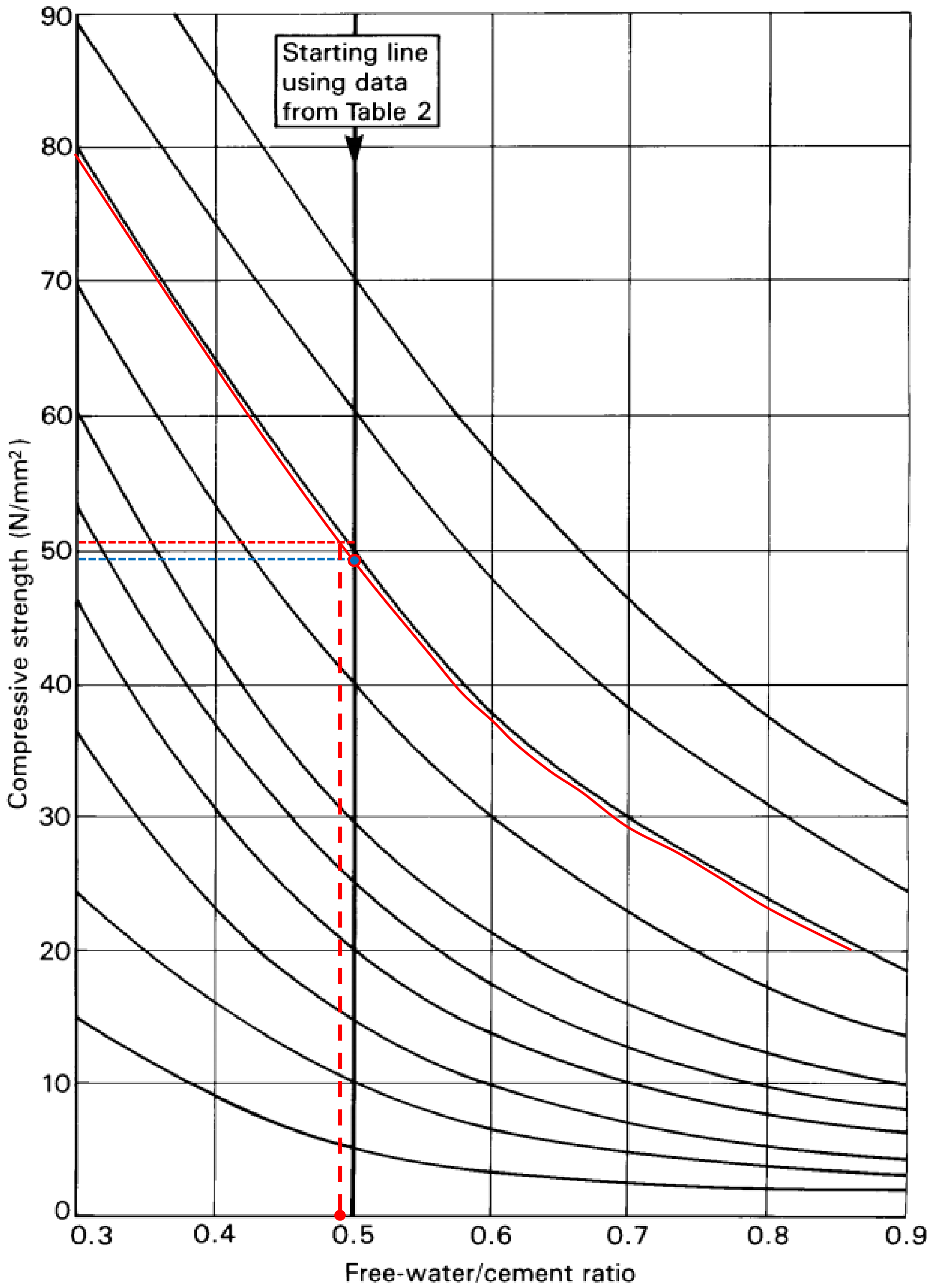
Quantities	Cement (kg)	Water (kg or litres	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm
per m3 (to nearest 5kg)	**510**	**250**	**900**	**650**



BRE Figure 3

Table 2 Approximate compressive strengths (N/mm^2) of concrete mixes made with a free-water/cement ratio of 0.5

Cement strength class	Type of coarse aggregate	Compressive strengths (N/mm^2)			
		Age (days)			
		3	7	28	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61



Starting line using data from Table 2
Compressive strength (N/mm²)
90
80
70
60
50
40
30
20
10
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Free-water/cement ratio

BRE Figure 4

Table 3 Approximate free-water contents (kg/m³) required to give various levels of workability

Slump (mm)		0–10	10–30	30–60	60–180
Vebe time (s)		>12	6–12	3–6	0–3
Maximum size of aggregate (mm)	**Type of aggregate**				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

Note: When coarse and fine aggregates of different types are used, the free-water content is estimated by the expression:

$$\tfrac{2}{3} W_f + \tfrac{1}{3} W_c$$

where W_f = free-water content appropriate to type of fine aggregate
and W_c = free-water content approporiate to type of coarse aggregate.

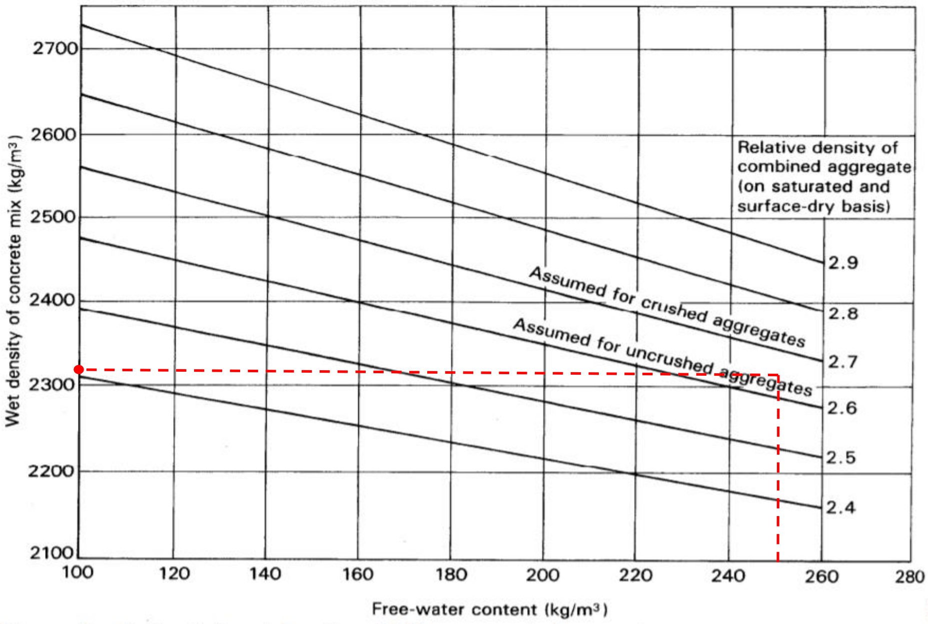


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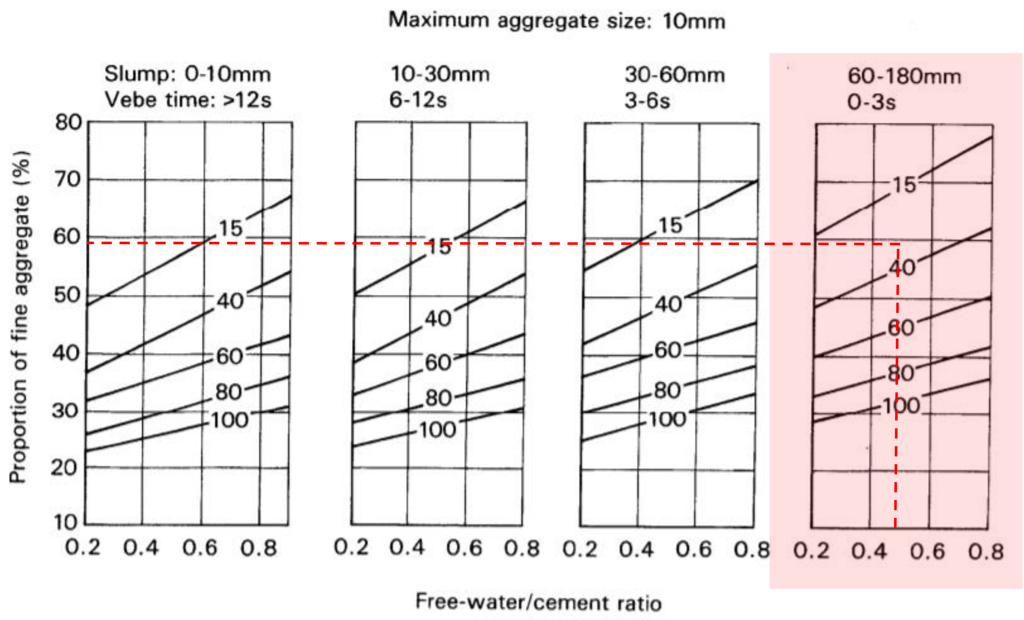
Figure 5 Estimated wet density of fully compacted concrete

BRE Figure 5


Maximum aggregate size: 10mm
Slump: 0-10mm
Vebe time: >12s
10-30mm
6-12s
30-60mm
3-6s
60-180mm
0-3s
Proportion of fine aggregate (%)
80
70
60
50
40
30
20
10
15
40
60
80
100
0.2 0.4 0.6 0.8
Free-water/cement ratio

BRE Figure 6